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HEAVY FLAVOR PHYSICS AND CP VIOLATION

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1 Overview

Assuredly one of the deep mysteries of particle physics is why there are families — apparently blind, unnecessary repetitions of e^-, ν_e, u, d. The existence of families gives rise to many of the free parameters of the Standard Model, in particular the four parameters that describe the Cabibbo-Kobayashi-Maskawa (CKM)[1] matrix, the masses of the c, s, t, and b quarks, and the masses of the μ and τ leptons. A determination of all these parameters is needed if for no other reason than to fully define the Standard Model. Further, patterns evident among the masses and matrix elements may provide clues to guide the development of a theory to explain families, and their values certainly provide constraints on attempts at such a theory.

Many quantities which can be measured in several quite different experiments are related to the same parameter in the Standard Model. Physics beyond the Standard Model could be revealed by inconsistencies in the results obtained in different experiments. In addition physics beyond the Standard Model can lead to signals much larger than those predicted by the Standard Model, especially for channels that are forbidden or highly suppressed in the Standard Model. The search for, and eventually the measurement of, partial rates for very rare decays offers the opportunity to test predictions of the Standard Model at the quantum loop level; significant deviations would point to the presence of new physics.

Searches for both these types of discrepancies, inconsistencies between parameters measured in different channels and larger than predicted signals for forbidden or loop-suppressed decays, provide important low-energy windows on the high-energy-scale physics beyond the Standard Model and should be energetically pursued. To date the searches for rare decays have been pursued to the most stringent limits in K decays, where the extremely small Standard Model predictions leave many orders of magnitude to search for non-Standard effects. However searches in D, B and tau decays probe possibly different coupling sectors and thus interesting constraints on models also come from these searches, despite the fact that at first glance the numbers appear less stringent.

The existence of three families of quarks is by now well established, and with that the existence of a nontrivial phase in the most general matrix of weak coupling constants (the CKM matrix). Consequently, unless there is some symmetry which forces this phase to be identically 0° or 180°, there will be CP violation. However, while the occurrence of CP violation should not be viewed as unusual in the context of the Standard Model, it remains to be seen whether this phase is indeed the source of CP violation in nature.

The CKM matrix can be written as

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \tag{1}$$

$$\simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4) \tag{2}$$

In the above expression $\lambda = \sin(\theta_{Cabibbo})$, and the three remaining parameters A, ρ, and η encode the remaining two weak mixing angles and the phase that introduces *CP* violation. This parametrization, due to Wolfenstein [2], is frequently used in discussing *CP* violating effects. It is given here up to terms of order λ^3; higher order terms in λ can be calculated from the Unitarity requirements. The *CP* violation in the Standard Model all arises from the parameter η in this matrix and vanishes if $\eta = 0$. We introduce this notation here because experimental results, particularly those on *CP* violation, are often presented in terms of the Wolfenstein parameters. Determination of the magnitudes of CKM matrix elements, obtained independently of *CP* violation measurements, are a necessary preliminary to the test of the hypothesis that *CP* violation is "explained", (*i.e.*, parametrized) by the phase in the CKM matrix. Further, they are an essential component of the general program to overdetermine Standard Model parameters and thereby search for effects due to physics beyond the Standard Model.

CP violation, while readily accommodated in the three–generation Standard Model with the appearance of η in the CKM matrix, remains one of the least understood aspects of particle physics. There is as yet no evidence that η is in fact the only or even the principal source of the observed *CP* violation in *K* decays. Cosmologists attempting to understand the dominance of matter over antimatter in the universe generally agree that it is unlikely that the Standard Model with a single Higgs multiplet can provide sufficient *CP* violation to drive a mechanism for baryon number generation at the weak scale that can explain the observed baryon to entropy ratio in the universe [3]. Furthermore baryon generation at higher temperatures, for example at the grand unification scale must be protected by special symmetries to avoid dilution by baryon-number-violating effects that continue to occur in most models at all temperatures above the weak scale. Thus it is extremely important and interesting to study all possible sources of *CP* violation, in order to find what mechanisms are at work in this physics.

As with the quark sector, so in the lepton sector the family structure and conservation laws of lepton flavor are little understood, and may in fact be only approximate in models beyond the Standard Model. Once again it behooves us to study the parameters of this sector with as much redundancy as possible to seek pointers to non-Standard effects. The search for forbidden processes, exemplified by the search for decays violating lepton number, holds forth the possibility of revealing a "smoking gun" of evidence that *there is* physics beyond the Standard Model.

In the Standard Model the tau is a heavy electron-like particle, which comes with its partner, the left-handed tau neutrino. From the measurements of the *Z* width at SLC and LEP [4] we know that the tau lepton is the heaviest sequential lepton, *i.e.,* the last charged lepton with a light neutrino. Many extensions of the Standard Model contain mass–dependent couplings, and therefore, predict much larger deviations from the standard theory in tau data than in the muon sector, so again measurements that appear redundant in the Standard Model need to be pursued.

In addition to the extraction of the fundamental Standard Model parameters and searches for non-Standard effects related to heavy quark and lepton sectors there is also considerable physics to be learned from studies of spectra and branching ratios to particular decay channels of heavy flavor mesons and baryons, and also from hadronic decays of the tau. Recent developments in the theory of these decays include heavy quark effective theory which provides a systematic expansion in $1/m_q$ about a rigorous infinite quark mass limit. Improved lattice calculational techniques are also likely to shed new light on hadronic parameters relevant to these measurements such as hadronic matrix elements and decay form factors. Much remains to be learned in this area, both on the theoretical side in improved calculations and on the experimental side in new or improved branching ratio and spectrum determinations.

In what follows Section 2 discusses the determination of Standard Model parameters, Section 3 is devoted to *CP* violation, Section 4 to rare and forbidden decays and Section 5 to hadronic physics effects in heavy flavor decays. Finally in Section 6 we discuss the present and proposed facilities for furthering these investigations.

2 Standard Model Parameters and Tests

Below we discuss the determination of the CKM matrix, the determination of heavy quark masses, and detailed studies within the tau–lepton sector.

2.1 CKM Matrix Determination

Given the constraint of unitarity, a 3-family CKM matrix is described by 4 parameters, three angles and a phase. The Standard Model provides no guidance as to their values. Tree-level processes involving the first two families have been used to determine one of these four parameters, the Cabibbo angle, which essentially determines V_{ud}, V_{us}, V_{cd}, and V_{cs}. Tree-level processes involving b decay can determine two more, $|V_{cb}|$ and $|V_{ub}|$, although obtaining reasonable precision on $|V_{ub}|$ is not easy. The fourth parameter is somewhat of a dilemma. It can be obtained from *CP* violation measurements, as discussed in Section 3. However, one would like to determine the CKM matrix *without* using such measurements, to obtain a sharper test of the origin of *CP* violation. From Eqs. (1) and (2) it is clear that measurements of $|V_{ud}|$ and $|V_{td}|$ determine ρ and η and hence the phase in the CKM matrix. In principle, this is measurable from tree-level decays of top, but in practice such an approach seems very far off. So, one resorts to loop processes involving b and s quarks. Below we discuss determination of $|V_{cb}|$, $|V_{ub}|$ and $|V_{td}|$. ($|V_{tb}|$ and $|V_{ts}|$ are obtained from unitarity, to much better accuracy than is possible from their direct measurement.) The present knowledge of the CKM matrix is summarized in the Particle Data Group report [1].

2.1.1 $|V_{cb}|$

Two methods have been used to determine $|V_{cb}|$. Both work. At this stage it is a matter of improving accuracy.

- From average lifetime and inclusive semileptonic decay branching ratio.

The semileptonic width of the b quark, in the naive parton model, is

$$\Gamma(b \to c\ell\nu) = \frac{G_F^2 m_b^5}{192\pi^3}|V_{cb}|^2 f_1\left(\frac{m_c}{m_b}\right) \tag{3}$$

Inclusive lifetime measurements now have an accuracy of ± 4%, and inclusive semileptonic decay branching ratio measurements an accuracy of ± 3%, which implies a determination of $|V_{cb}|$ to $\pm\ 2\frac{1}{2}\%$. There are perturbative QCD corrections to Eq. (3), which are not a problem. The problem is the factor m_b^5, because what to use for m_b is not clear. An uncertainty of 200 MeV in m_b translates into a ± 10% uncertainty in $|V_{cb}|$. If the difference $m_b - m_c$ is assumed known, this uncertainty drops to ±4%. Theoretical work is needed here, to determine m_b and m_c, and to account for the kinetic energy of the b quark inside the hadron [5,6].

- From $B \to D^*\ell\nu$, extrapolating to zero-recoil point.

At the zero-recoil point, the value of the form factors can be determined, from Heavy Quark Effective Theory (HQET, see Section 5.1), to an accuracy of ± 4%, implying a theoretical limitation on the determination of $|V_{cb}|$ of ± 4%, with opportunities for improvements [6,7]. The problem with this method is that the zero-recoil point is at one end of the physically allowed range. Consequently, the rate cannot be measured by interpolating from both sides of the point of interest, but only by extrapolating from one side. Improvements to a determination of $|V_{cb}|$ by this method will come both from experimental work (higher statistical accuracy, so the extrapolation can be done more accurately), and from theoretical work (understanding the shape of the form factor near the zero-recoil point, to guide the extrapolation, and determining the form factor at zero recoil more accurately).

2.1.2 $|V_{ub}|$

Four methods for determining $|V_{ub}|$ will be discussed. So far only the first has given useful results.

- Lepton spectrum near the endpoint.

By measuring the yield of leptons beyond the endpoint for $b \to c\ell\nu$, both CLEO [8] and ARGUS [9] have established that the process $b \to u\ell\nu$ occurs, and therefore $|V_{ub}|$ is non-zero. Unfortunately, there are major theoretical problems in determining what fraction of the spectrum from $b \to u\ell\nu$ lies in this endpoint region [10]. Current theoretical understanding limits the accuracy of a determination of $|V_{ub}|$ by this method to about ± 25%, but recent work with HQET shows promise of improving the situation [11].

- Exclusive Semileptonic Decays, with Tagged B's.

If one of the B's in a $B\bar{B}$ event at the $\Upsilon(4S)$ is fully reconstructed, then the four-momentum of the second B is known, and its exclusive semileptonic decays can be reconstructed in spite of the neutrino. Given a sufficiently large sample of $B\bar{B}$ events with one B fully reconstructed (a "tagged B" sample), one could observe the charmless exclusive decays $B \to \pi\ell\nu$ and $B \to \rho\ell\nu$. HQET relates these decays to $D \to \pi\ell\nu$ and $D \to \rho\ell\nu$. If these D decays have also been measured, one can extract $|V_{ub}/V_{cd}|$. (Since the D decay measurements are far easier than the B decay measurements, they will likely be done far sooner.)

The major stumbling block to this method is obtaining a sufficiently large tagged B sample. The technique requires that the $B\bar{B}$ pair be produced at the $\Upsilon(4S)$, and so rates will be those of e^+e^- facilities. CLEO obtains ~ 1000 tagged B's/fb^{-1}. The branching ratios for $B \to \pi\ell\nu$ and $B \to \rho\ell\nu$ are $\sim 10^{-4}$. So a reasonable measurement (100 events) requires 10^6 tagged B events (either ~ 1000 fb^{-1} or substantial improvements in B reconstruction efficiency). For scale, CLEO has logged 1 fb^{-1}/yr for the past few years, and a B Factory running at design luminosity would log 30 fb^{-1}/yr. Said more directly, in its simplest form this approach won't work.

- "Neutrino Detection".

Given a sufficiently hermetic detector operating at the $\Upsilon(4S)$, one can use the missing 4-momentum of the event to select events for which the only undetected particle is a single neutrino. Then, taking the missing 3-momentum of the event to be that of the neutrino, one can study $b \to u\ell\nu$ decays in two ways.

(a) Exclusive Semileptonic Decays. Given the neutrino, $B \to \pi \ell \nu$ and $B \to \rho \ell \nu$ can be reconstructed using the standard approach that works for hadronic decays. Sample sizes of 20 fb^{-1} might be adequate, a considerable reduction over that required with method 2. (At an asymmetric collider, one may be able to use the vertexing of the two B's to reconstruct these exclusive modes even without a fully hermetic detector.)

(b) Inclusive Semileptonic Decays. Given the neutrino and the lepton, one can determine, to reasonable accuracy, the mass M_X in a decay $B \to X \ell \nu$. (If the B were at rest, M_X could be precisely determined. The B momentum of 300 MeV/c, with unknown direction, smears the determination of M_X by a few hundred MeV.) In this way, one can separate $B \to X_u \ell \nu$ from $B \to X_c \ell \nu$, for $M_{X_u} \overset{\sim}{<} 1.6$ GeV. This makes accessible a much larger fraction of the phase space for $b \to u \ell \nu$ than is accessible with method 1.
Preliminary work with "neutrino detection" by CLEO shows promise.

- Exclusive Hadronic $b \to u$ Decays.

CLEO, with 2 fb^{-1}, has a hint of $\bar{B}^0 \to \pi^+ \pi^-$ [12]. With a sample of 20 fb^{-1}, several charmless hadronic decays will be measured. However, it is questionable whether theory will be adequate to the task of obtaining $|V_{ub}|$, at the sub-25% level, from measurements of hadronic decays.

2.1.3 $|V_{td}|$

Five methods for determining $|V_{td}|$ will be discussed. So far, only the first has given useful results.

- $B^0 - \bar{B}^0$ mixing, m_t, and f_B from theory.

The $B^0 - \bar{B}^0$ mixing parameter $x_d = \Delta M/\Gamma$, measured to ± 15% [13,14], is related to $|V_{td}|$ via the expression [15]:

$$x_d = \frac{G_F^2}{6\pi^2} m_t^2 \tau_B B_B f_B^2 M_B |V_{td} V_{tb}^*|^2 \frac{A(z_t)}{z_t} \eta_{QCD}, \tag{4}$$

with $z_t = m_t^2/M_W^2$, and $A(z_t)$ a known function. The QCD correction factor η_{QCD} is known to ± 5%, posing no problem. The problems are the top quark mass m_t and $B_B f_B^2$, where B_B is the "bag parameter" arising from the vacuum insertion approximation, and f_B is the B meson decay constant. At present m_t is known to ± 10%, and it is reasonable to expect improvements to ± 5% soon. Then the only problem will be $B_B f_B^2$.

There are calculations of B_B and of f_B^2, by lattice gauge techniques and other methods [16]. Currently these determine $\sqrt{B_B} f_B$ to perhaps 20 – 25 %, and this uncertainty dominates the error on $|V_{td}|$ extracted in this way. Significant improvements in this method depend on improvements in lattice gauge calculations (in particular better understanding of the quenched approximation), and also on improved measurements of f_D and/or f_{D_s}, which can provide tests of the theoretical calculations.

- Ratio of $B_d - \bar{B}_d$ and $B_s - \bar{B}_s$ Mixing.

An expression similar to Eq. (4) applies to $B_s - \bar{B}_s$ mixing. Taking ratios of equations, one has

$$\frac{x_d}{x_s} = \frac{\tau_{B_d}}{\tau_{B_s}} \frac{B_{B_d}}{B_{B_s}} \frac{f_{B_d}^2}{f_{B_s}^2} \left| \frac{V_{td}}{V_{ts}} \right|^2 . \tag{5}$$

Now, theory is only required to calculate the ratio $(B_{B_d} f_{B_d}^2)/(B_{B_s} f_{B_s}^2)$, which should pose much less of a problem, since many common uncertainties cancel in the ratio. However, measuring $B_s - \bar{B}_s$ mixing is a major challenge. Because x_s is expected to be large, it is necessary to measure the time evolution of the mixing process. This might be done with SLD, at LEP, at an asymmetric B Factory or with a hadron collider. These experiments may be able to determine x_s if it is smaller than 20. Beyond that value, a measurement will be extremely difficult.

- $b \to d\gamma$.

Just as the QCD-uncorrected process $b \to s\gamma$ has a width proportional to $|V_{ts} V_{tb}^*|^2$, so the QCD-uncorrected process $b \to d\gamma$ has a width proportional to $|V_{td} V_{tb}^*|^2$ (see Section 4.3.2). Thus, one might expect, for example, that $Br(B \to \rho\gamma)/Br(B \to K^*\gamma)$ should equal $|V_{td}/V_{ts}|^2$, times a known kinematic correction factor. One needs to worry about the large QCD correction handled by renormalization group techniques, and about long distance effects. The former are believed to be under control [17]. The size of long distance effects is currently a matter of intense debate [18], [19], but there is agreement that $b \to d\gamma$ contains information on $|V_{td}|$, and that the theoretical work needed to extract this information is quite feasible. (Measurement of $D \to \rho\gamma$ would provide an important test of the theoretical understanding.) This would mean that a measurement of $b \to d\gamma$ exclusive decays will give V_{td}. With 3 fb^{-1}, CLEO has an upper limit [20], and with 20 times more data (2 years of design-level B Factory running), would have a useful measurement.

The processes $b \to s \ell^+ \ell^-$ and $b \to d \ell^+ \ell^-$ (*i.e.*, the same processes but with virtual photons) have smaller QCD corrections. Should the QCD corrections prove to be a major stumbling block for $b \to d\gamma$, then these might be more suitable. In particular, an eventual measurement of $(B^- \to \pi^- \mu^+ \mu^-)/(B^- \to K^- \mu^+ \mu^-)$, at a hadron collider, seems feasible.

- Determining f_B from $B^- \to \tau^- \nu$ or $B^- \to \mu^- \nu$.

These decays have widths proportional to $f_B^2 |V_{ub}|^2$, and thus a successful measurement, combined with $B^0 - \bar{B}^0$ mixing (and theory for B_B) gives one $|V_{ub}/V_{td}|^2$, which would be very nice. The expected branching ratio for $B \to \tau\nu$ is $\sim 10^{-4} - 10^{-5}$, while that for $B \to \mu\nu$ is smaller by a factor of 230. The present experimental upper limit on $B \to \tau\nu$ is $\sim 1/4\%$ [21]. This limit was obtained with a 3 fb^{-1} data sample, so it is clear that improvements in technique are required in addition to increases in luminosity. The separate vertexing provided by an asymmetric machine may help to reduce backgrounds and so improve this situation, but hermiticity will still be a major problem.

- $K^+ \to \pi^+\nu\bar{\nu}$.

This process, proportional to $|V_{td}|^2$, has an expected branching ratio in the range of $(0.5 - 3)\times 10^{-10}$. Unlike some other kaon decays, long distance corrections are very small and theoretical uncertainties are at the 10% level [22]. The current upper limit on the branching ratio is 3×10^{-9}. If the actual value is near 2×10^{-10}, then experiment BNL787 expects a measurement to ± 30%, giving $|V_{td}|$ to ± 15%. Upgrades in the detector and increases in beam intensity could improve the accuracy a factor of two.

Summary:

- Two methods have been used to give $|V_{cb}|$. Both work, and give determinations in the $\pm 5\%$ range. Accuracy will improve with more data and with theoretical refinements.
- For $|V_{ub}|$, "neutrino detection" is the most promising approach, with "proof of concept" by CLEO imminent.
- There are 5 methods which can give $|V_{td}|$. None is easy, and none is direct. All should be pursued. Should two methods give different answers, that could indicate additional particles in the loops, and would strongly suggest new physics.

2.2 Heavy Quark Masses

The problem of definition of quark masses has many implications for theoretical predictions. For example, meson decay rates for free quarks depend on the fifth power of the quark mass and thus predictions are sensitive to small shifts in this value. However, since quarks cannot be isolated there is no direct connection between the Lagrangian mass parameters that appear in such perturbative calculations of quark processes and any measurable quantity. Even in the context of perturbation theory there is a plethora of definitions in the literature, since the quark mass parameter is convention and renormalization scale dependent. Further it is difficult to relate these parameters to measurable quantities, especially in the

Current algebra relationships between meson masses and Lagrangian parameters (which lead to the old term "current quark masses" for these quantities) also leave some uncertainties because of higher order corrections, both from weak interaction perturbation theory and from corrections to the chiral limit. Lattice calculations of spectra can determine mass parameters on the lattice, and recently there has been substantial progress in relating these quantities to perturbatively-defined and to experimentally-measured quantities. Recent progress in heavy quark effective theory has introduced yet another definition of the quark mass in terms of the equation

$$M_Q = m_q + \bar{\Lambda} - \frac{\lambda_1 + 3\lambda_2}{2m_q} + \mathcal{O}(1/m_q^2) \qquad (6)$$

where M_Q is the pseudoscalar meson mass, m_q is the quark mass, $\bar{\Lambda}$ is a parameter which may be interpreted as the energy of the light degrees of freedom, λ_1 parametrizes the kinetic energy of the heavy quark inside the hadron, and λ_2 parametrizes the effects of the chromomagnetic moment operator. One readily determines λ_2 from the vector-pseudoscalar mass difference, since for vector mesons the above equation is modified by the replacement of $3\lambda_2$ with $-\lambda_2$. $\bar{\Lambda}$ and λ_1 cannot be so readily determined, and are the objects of current theoretical activity, as are the $1/m_q^2$ corrections. Systematic treatment of this type, and other similar work starting from lattice calculations of meson properties, offer perhaps the best approach yet to the problem of the relationship of theoretically defined quark mass parameters to experimentally measured quantities. This problem is one where further theoretical work is needed, to determine the most precise way to extract these important parameters from experiment.

The experimental inputs used so far are the masses of the $q\bar{q}$ bound states and the masses of the heavy-light mesons. A measurement of the photon energy spectrum in $b \to s\gamma$ would provide additional information on the b quark mass; at the naive spectator model level $\langle E_\gamma \rangle = m_b/2$. HQET calculations bear this result out, giving small corrections [23,24]. Extrapolating from studies with CLEO [25], a 30 fb^{-1} data sample would determine m_b to ± 100 MeV (statistical error only).

For the top quark, which decays before bound states form, the relationship between the Lagrangian parameter in perturbation theory and predicted top-quark production cross sections is more direct and hence there is less ambiguity in the definition of the top quark mass parameter. (Determination of the top quark mass is considered by the Electroweak Working Group.)

2.3 Tau parameters and Tests

Thanks to its mass, the tau is the only lepton that can decay to hadrons (*i.e.*, $\bar{u}d$ and $\bar{u}s$ quark pairs). This provides an opportunity to study strong interaction phenomena in weak charged–current decays in particularly clean experimental and theoretical environments. When approached in an inclusive way, semi-hadronic decays of the tau provide interesting tests of perturbative QCD and give a determination of the scale of strong interactions. The phenomenology of low–mass hadronic resonances finds a rich, and often unique, source of information in individual semi-hadronic tau decays modes.

The tau lepton also plays a special role at LEP and SLC experiments performed at the Z peak, since it is the only lepton that copiously decays inside the apparatus, offering an independent method of measuring the Lorentz structure of weak neutral currents via lepton–polarization measurements.

We discuss lepton universality tests and measurements of Lorentz structure of charged and neutral weak currents involving τ's below. Searches for flavor violating and other rare decays are discussed in Section 4. Measurements of the tau neutrino mass and searches for neutrino mixing are described by the Neutrino Working Group. QCD tests in semi-hadronic decays of tau are covered in Section 5.

2.3.1 Lepton Universality Tests

- Purely leptonic decays

The Standard Model predicts that couplings of leptons to charged and neutral currents are flavor independent. Test of this assumption can be obtained by comparison of the electronic decay of tau, $\tau \to \nu_\tau e \bar{\nu_e}$, to muon decay, $\mu \to \nu_\mu e \bar{\nu_e}$. These two processes differ only by different phase-space (dependence on m_τ and m_μ) and possibly different couplings of τ and μ (g_τ and g_μ). In comparison of the measured decay branching fractions, one also has to include different lifetimes (τ_τ and τ_μ) and radiative corrections (R_c):

$$\left(\frac{g_\tau}{g_\mu}\right)^2 = \frac{\tau_\mu}{\tau_\tau}\left(\frac{m_\mu}{m_\tau}\right)^5 \frac{B(\tau \to \nu_\tau e \bar{\nu_e})}{B(\mu \to \nu_\mu e \bar{\nu_e})}(R_c) \qquad (7)$$

Since each of the μ parameters is known with accuracy roughly three orders of magnitude better than the corresponding τ parameters the above test is totally dominated by experimental errors for τ lepton. Theoretical uncertainty is only of the order of 0.01%. Using the world average values, $\tau - \mu$ universality is now tested to about 1%: $g_\tau/g_\mu = 0.996 \pm 0.010$ [26]. There has been significant progress in accuracy of the measurements of τ parameters over last few years, and we are now close to the accuracy reached in $\mu - e$ universality tests: $g_\mu/g_e = 1.003 \pm 0.003$. (Further improvement on this ratio can be expected from a new branching ratio measurement at TRIUMF). At present, the contribution to the error on g_τ/g_μ are as follows: $\Delta\tau/\tau = 0.8\%$, $5\Delta m_\tau/m_\tau = 0.08\%$, and $\Delta B_e/B_e = 0.6\%$. The tau mass has been precisely measured by the BES experiment at the Beijing collider (BEPC), which operates at the τ–production threshold [27]. Limited further improvement is possible by devoting more beam time for this measurement at BEPC, in combination with improved beam-energy determination, or by construction of a τ–charm factory.

There are two complementary paths to improve tau lifetime measurements: experiments at the Z peak which are statistics limited; measurements at intermediate e^+e^- collision energies (CESR or future B Factories), which are also systematics limited. Increased statistics at LEP, and upgrade of the CLEO-II detector to include a silicon vertex detector and upgrade of CESR to higher luminosity will yield improvements in the lifetime measurements in next few years. Asymmetric B Factories are also expected to play an important role here. The most precise measurement of B_e has been obtained by CLEO [28]. Even though, there is some room for improvement, CLEO measurements will eventually be limited to $\sim$ 0.5% by the error on theoretical cross section for $\tau^+\tau^-$ and Bhabha events (which are used to determine the luminosity). Even if these theoretical limitations are overcome by more precise calculations, improved measurement would require a dedicated effort to control experimental systematics at this level. High statistics measurement at the Z peak offers perhaps more attractive route to improve B_e measurement in the long run, because theoretical normalization errors are already smaller and because of possibility of directly counting number of produced tau leptons (better separation from backgrounds).

- Semi-hadronic decays

An independent test of $\tau - \mu$ universality can be obtained from comparison of $\tau \to \pi\nu_\tau$ with $\pi \to \mu\bar{\nu_\mu}$ (or $\pi \leftrightarrow K$). At present this test is limited to precision of about 2% due to the error on $B(\tau \to \nu_\tau\pi, K)$. Improvements are expected from both LEP experiments and CLEO. A τ–charm factory which would operate at the τ-pair production threshold, where two body decays can be isolated from other τ decays by kinematic constraints, may be able to achieve a somewhat better measurement, perhaps down to a fraction of a percent.

- Tests at hadron machines

Universality of $\tau - \mu - e$ couplings can be also tested in decays of $W \to l\bar{\nu_l}$. So far, these measurements have rather large errors: 8% on g_τ/g_e (UA1+UA2). CDF and DØ are expected to improve the accuracy of these measurements to about 4% (See the Electroweak Working Group report).

2.3.2 Lorentz Structure of the Weak Currents

- Purely leptonic decays

The Lorentz structure of four-fermion interactions in τ decays can be studied in full analogy with μ decays. The charged lepton momentum spectrum and angular distribution in the τ rest frame can be written in the most general form which allows for scalar, vector and tensor interactions with help of the Michel parameters

$(\rho, \eta, \xi, \delta)$ [29]:

$$\frac{d\Gamma}{dx\, d\cos\vartheta} \propto x^2 \left[12(1-x) + \rho\tfrac{4}{3}(8x-6) + 24\eta\frac{m_l}{m_\tau}\frac{1-x}{x}\right] \\ -\xi\mathcal{P}_\tau \cos\vartheta\, x^2 \left[4(1-x) + \delta\tfrac{4}{3}(8x-6)\right] \tag{8}$$

where $\mathcal{P}_\tau$ is τ lepton polarization, $x = P_l/P_{max}$, and ϑ is an angle between τ spin and $\vec{P_l}$. The Standard Model ("V-A") predicts: $\rho = \frac{3}{4}$, $\eta = 0$, $\xi = 1$, and $\delta = \frac{3}{4}$. Values of these parameters are sensitive to small admixtures of scalar or right-handed intermediate bosons, and thus their measurement provides a search for new physics.

The spectral shape parameters, ρ and η, are measured from fits to the observed electron and muon spectra in τ decays. Sensitivity to η parameter is better in $\tau \to \nu_\tau \mu \bar{\nu_\mu}$ because this parameter enters multiplied by the m_l/m_τ ratio. Since the η parameter changes also the overall rate, precision measurements of B_e and B_μ allow determination of η. The decay asymmetry parameters, ξ and δ, are more difficult to measure because they depend on tau polarization which averages out to zero when integrated over all angles in $\gamma \to \tau^+\tau^-$ production. Thus, measurements at lower energy e^+e^- colliders must study correlations in leptonic decays of the two τ's in the event. Measurements using $Z \to \tau^+\tau^-$ have an advantage of average $\mathcal{P}_\tau \neq 0$. However, usually the value of $\mathcal{P}_\tau$ and not the Michel parameters are the subject of measurements at LEP and SLC.

The measured Michel parameters in τ decays [29], $\rho = 0.733 \pm 0.026$, $\eta = -0.010 \pm 0.052$ and $|\xi| = 0.90 \pm 0.18$, are consistent with the Standard Model but far less precise than corresponding measurements in muon decays: $\rho = 0.752 \pm 0.003$, $\eta = -0.007 \pm 0.013$, $\xi = 1.003 \pm 0.008$ and $\delta = 0.745 \pm 0.004$. The MEGA experiment at LAMPF will further improve measurements of ρ parameter in muon decays. The best measurements in τ decays come so far from the ARGUS experiment at DORIS. CLEO and LEP should soon improve these measurements by analysis of already recorded data. Further improvements are likely to be systematics limited and will require a dedicated effort. A tau-charm factory would be the best suited for precision measurements of the Michel parameters because sensitivity to the Michel parameters is best in the tau rest frame. Also cross-feed from the other τ decays can be better controlled at the τ-pair production threshold. Precision of a fraction of a percent is achievable at a τ-charm factory.

- Semi-hadronic decays

Semi-hadronic decays offer independent opportunity to test V-A coupling at the $\tau - W - \nu_\tau$ vertex. Studies of energy and angle correlations among final state hadrons from decays of both τ's in the event allow one to measure tau neutrino helicity (-1 in the Standard Model). Measurements with accuracy of a few percent are now available from ARGUS, CLEO-II and ALEPH experiments.

- Neutral currents

At LEP and SLC, tau decays act as polarimeter for measurement of lepton polarization in $e^+e^- \to Z \to \tau^+\tau^-$. This allows the determination of V and A couplings to Z of τ's and e's independently (test of $\tau - e$ universality). Furthermore, determination of the relative sign of the V and A couplings is possible (not available from other measurements at Z). The Standard Model predictions for these couplings depend on top quark and Higgs masses (See the Electroweak Working Group report). These measurements are part of the core program at LEP and SLC. LEP experiments have larger data samples. The SLD experiment at SLC offers measurements with a different set of systematics. The measurements at the SLC also benefit considerably from the electron beam polarization.

3 *CP* Violation and *T* Violation

For neutral pseudoscalar mesons with non-trivial flavor content the mass eigenstates are linear combinations of the flavor eigenstates

$$X_{1,2} = (pX^0 \pm q\overline{X}^0)/\sqrt{pp^* + qq^*} \tag{9}$$

where X^0 may be K^0, D^0, B^0 etc. If *CP* were an exact symmetry then these states would have $p = q = 1$, *i.e.*, the mass eigenstates would also be *CP*-eigenstates. However, as is well known in the kaon system, *CP*-violating phases in the mixing amplitudes can introduce deviations from this form. In principle this is true for vector as well as pseudoscalar mesons, but since the former decay strongly there is never a chance to observe the effects of mixing in such states. Similarly, in the Standard Model, mixing in the D^0 states is negligible, *i.e.*, they decay before any appreciable mixing effects can be observed.

In general one can distinguish three major types of *CP* violation [30]. Firstly there are two distinct categories of indirect *CP* violation. Indirect *CP* violation effects can arise because of interference between the amplitudes for the decay of a neutral meson to a final state of definite *CP* and the decay to that same state after mixing of the neutral meson with its antiparticle. This effect has been observed in neutral K decays, for example to two pions. Similar effects could also occur in the neutral D and B systems, although in the Standard Model the prediction is that such effects are much smaller in the D system, because of the smaller mixing in that system. The second type of indirect *CP* violation occurs if mixing effects in the neutral K, D, or B sectors lead to a deviation from unity for the absolute value of the ratio of the weights (p and q) of the two *CP*-conjugate mesons in the mass eigenstates of the system ($|q/p| \neq 1$). This then leads to *CP*-violating rate asymmetries in the decay of neutral mesons to final states of definite flavor. Effects of this latter type are also observed in the K system, for example the asymmetries in the semileptonic decay channels are of this type. However, such effects are expected to be very small in the B system in the Standard Model.

The third type of *CP* violation is direct *CP* violation, *i.e.*, that due to a difference between the magnitude of the decay amplitude A for a particular process and the *CP*-conjugate amplitude $\overline{A}$, $|A/\overline{A}| \neq 1$. This requires that there be at least two independent contributions to the amplitude that contribute with different strong phases and different weak phases [31]. In the Standard Model the tree diagrams for a given decay all contribute with the same weak phase and thus direct *CP* violation effects occur only when there are loop (penguin) contributions. Direct *CP* violation can occur in charged decays, in neutral decays to flavor tagged eigenstates or in neutral decays to *CP* eigenstates. No convincing evidence for direct *CP* violation has yet been established.

Discussions of *CP* violation in the K system in general do not make a strong distinction between the two types of indirect *CP* violation, since both occur in that system. However note that the first type of indirect process – interference of mixed and unmixed decays to *CP* eigenstates in the neutral meson sector – can occur even when both $|A/\overline{A}| = 1$ and $|q/p| = 1$. It requires only that the weak phase of the mixing be different from the weak phase of the decay amplitude. This is the predominant effect predicted by the Standard Model for B decays.

Since different models can give quite different predictions for the each of the three types of *CP* violation, and for the different strengths of expected effects in K, D and B systems, as well as in baryonic decays, there are a plethora of channels that need to be explored. Only by exploiting as many opportunities as possible to explore *CP* violating effects can we hope to unravel the mystery of its source and perhaps to understand thereby the baryon domination of the universe. This is a field where much remains to be learned.

3.1 CPT and T Violation

In addition it is interesting to ask what experimental limits can be set on the possibility of violations of CPT symmetry. CPT symmetry is fundamental and is an exact symmetry in any field theory [32], so any experimental evidence that it is broken would require a serious re-evaluation of our understanding of all particle processes. Thus searches for CPT non-conservation are in the interesting situation where there is a very small probability of success, but where it would certainly have very large effect on our understanding of particle physics if a convincing CPT-violating result were to be obtained.

CPT violating effects could be observed via small differences in particle-antiparticle masses and lifetimes. The proton-antiproton and electron-positron fractional mass difference is is less than approximately 4×10^{-8}, at 90% confidence level, which is not sufficiently accurate to provide a sensitive probe of CPT symmetry. The experimental situation is considerably better, however, in the K^0 sector. Defining

$$\eta_{+-} = \frac{A(K_L^0 \to \pi^+\pi^-)}{A(K_S^0 \to \pi^+\pi^-)} = \epsilon + \epsilon' \qquad (10)$$

$$\eta_{00} = \frac{A(K_L^0 \to \pi^0\pi^0)}{A(K_S^0 \to \pi^0\pi^0)} = \epsilon - 2\epsilon' \qquad (11)$$

$$\Phi_{+-} = Arg(\eta_{+-}),\ \Phi_{00} = Arg(\eta_{00}),\ \Delta\Phi = \Phi_{00} - \Phi_{+-}$$

it can be shown that [33]

$$\frac{m_{K^0} - m_{\bar{K}^0}}{m_K} \simeq (\frac{\Delta m}{m_K})\sqrt{2}|\eta_{+-}|\tan(\Phi_{+-} - \Phi_\epsilon + \Delta\Phi/3). \qquad (12)$$

Here $\Phi_\epsilon = Arg(\epsilon)$ and $\Delta m = 3.479 \times 10^{-6}$ eV is the $K_L^0 - K_S^0$ mass difference. This small value for Δm provides considerable leverage in testing CPT since this gives $\Delta m/m_K = 6.99 \times 10^{-15}$. Measurement of $(\Phi_{+-} - \Phi_\epsilon)$ and $\Delta\Phi$ therefore can provide a direct test of CPT violation. Current best measurements from FNAL which are at present the most sensitive to this effect are consistent with CPT symmetry, giving

$$\Delta\Phi = 0.67^\circ \pm 1.0^\circ, \qquad (13)$$

$$\Phi_{+-} - \Phi_\epsilon = -0.38^\circ \pm 1.1^\circ \qquad (14)$$

There is no particularly natural scale at which CPT symmetry might be violated. Theorists view renormalizable field theory as the low-energy limit of some more general theory which might not itself be a field theory, and which could in principle contain the seeds of CPT violation. Continued efforts on measurements of Φ_{+-}, Φ_ϵ, and $\Delta\Phi$ could yield a surprise of surely fundamental importance.

Given CPT invariance, T violation is equivalent to *CP* violation. One of the strongest available constraints on model building for beyond-Standard-Model *CP*-violating physics is the upper limit on the value of the T-violating neutron electric dipole moment $d_n < 1.2 \times 10^{-25}$ e cm [34]. In the Standard Model, despite the known *CP* violation, the prediction for this quantity is very small, $\leq 10^{-31}$ e cm [35]. However the introduction of other sources of *CP* violation into the theory can dramatically change this prediction [36]. Many models have been ruled out by their failure to keep this quantity smaller than the measured upper limit. Experiments searching for an effect due to such a moment should continue.

3.2 CP Violation in K Decays

So far, the only established laboratory manifestations of *CP* violation are the indirect effects in the decays of neutral K mesons, such as the observation of $K_L^0 \to \pi\pi$ decays. The Standard Model predicts also a direct *CP* violation due to the interference between tree and penguin amplitudes for weak decays. In the Standard Model direct *CP* violation would imply a non-zero phase in the CKM matrix, ($\eta \neq 0$ in the Wolfenstein parametrization), whereas indirect *CP* violation effects, of the types already observed in K decays, could occur in a model where all weak coupling decay amplitudes are real, ($\eta = 0$), and the only source of *CP* violation is a phase in the mixing amplitude coming from some non-Standard-Model contribution [37].

In the kaon system, the traditional way to look for direct *CP* violation is to measure the parameter ratio ϵ'/ϵ for the 2π decays of the neutral kaon. This amplitude is directly proportional to η but with a factor that is difficult to calculate; thus a non-zero value of ϵ'/ϵ will establish direct *CP* violation but to obtain a precise value for η will require improvement in calculational techniques, such as lattice calculations, for hadronic matrix elements. Progress continues to be made in this area. However, the value of ϵ' is suppressed for high values of m_t because of a cancellation between different contributions; estimates now are in the range of about $3 \times 10^{-3}\eta$ with about a factor of 2 uncertainty. For a recent review of the search for direct *CP* violation effects see [38]. The current experimental situation is ambiguous. One experiment (CERN NA31) reports a non-zero result [39]

$$\epsilon'/\epsilon = (23 \pm 6.5) \times 10^{-4}, \qquad (15)$$

while a second experiment (FNAL E731) sees a result consistent with zero [40]

$$\epsilon'/\epsilon = (7.4 \pm 5.9) \times 10^{-4}. \qquad (16)$$

Each of these experiments is now entering a second round of measurement with improved apparatus (FNAL E832 and CERN NA48). Clearly it is important to resolve this issue.

The other decays in the kaon system that hold promise for the detection of direct *CP* violation are the modes $K_L^0 \to \pi^0 l\bar{l}$ where l can be either e, μ, or ν [41]. For the charged lepton states, the branching ratio (proportional to $|\eta|^2$) are in the range of 10^{-11} - 10^{-12}. It is most interesting to note that these decay modes have both direct and indirect *CP*-violating contributions. Their ratio is not known but may be of order of unity. The direct piece is primarily a short-distance effect that can be fairly reliably calculated. The indirect *CP*-violating amplitude can be determined most reliably by a measurement of $K_S^0 \to \pi^0 e^+ e^-$. In the absence of this a measurement of the rate and form-factor in $K^+ \to \pi^+ e^+ e^-$ and $K^+ \to \pi^+ \mu^+ \mu^-$, plus Chiral Perturbation theory can determine this amplitude. There is also the *CP*-conserving amplitude that is potentially of the same size as the *CP*-violating one, coming from a $\pi^0\gamma\gamma$ intermediate state. This can be determined by measurements of $K_L^0 \to \pi^0\gamma\gamma$. Both the indirect and the *CP*-conserving contributions must be known so that the indirect *CP* effect, if observed, can be interpreted correctly. The latest Brookhaven, FNAL and CERN kaon results (*i.e.*, the M_{ee} spectrum of the $K^+ \to \pi^+ e^+ e^-$ and the $M_{\gamma\gamma}$ spectrum of the $K_L^0 \to \pi^0\gamma\gamma$ seem to indicate that these two amplitudes are small. An observation of $K_L^0 \to \pi^0 e^+ e^-$ or $K_L^0 \to \pi^0 \mu^+ \mu^-$ will thus be a very exciting opportunity to look into direct *CP* violation effect.

Perhaps the most theoretically attractive probe for direct *CP* violation in the K system is the decay $K_L^0 \to \pi^0 \nu\bar{\nu}$. Unlike virtually all other decays in the kaon system, the decay is essentially pure direct *CP* violating; its branching ratio is given approximately by

$$\begin{aligned} BR(K_L^0 \to \pi^0 \nu\bar{\nu}) &= 8 \times 10^{-11} (m_t/m_W)^{2.2} A^4 \eta^2 \\ &= 2 \times 10^{-10} \eta^2 \qquad (17) \end{aligned}$$

where A is the parameter that appears in V_{cb} in the Wolfenstein parametrization of the CKM matrix. Given the lack of theoretical ambiguity the measurement of this branching ratio would be one of the cleanest possible ways to extract η. Table 1 shows the current best limits from FNAL E799 [42,43].

Table 1: Limits on $K_L^0 \to \pi l\bar{l}$

Process	Limit
$K_L^0 \to \pi^0 e^+ e^-$	4.3×10^{-9}
$K_L^0 \to \pi^0 \mu^+ \mu^-$	5.1×10^{-9}
$K_L^0 \to \pi^0 \nu\bar{\nu}$	5.8×10^{-5}

It is important that these rare branching ratios be measured with whatever precision is possible. They afford one of the best ways of determining the parameter η directly and they will complement the eventual measurements of the angles of the unitarity triangle from neutral B decays. Ways to search for direct *CP* violation in strange quark decays other than neutral kaon decays include:

- a comparison of decay asymmetry parameters from hyperon and its *CP* conjugate antihyperon decays (A new search for this effect is planned at FNAL.) [44];
- a comparison of Dalitz slope difference of $K^+ \to \pi^+\pi^+\pi^-$ and $K^- \to \pi^-\pi^-\pi^+$ (The current limit is about 1%.); and
- a non-zero value of the transverse muon polarization in $K_{\mu 3}$ decay, which is a triple-vector correlation and

odd under time-reversal (thus *CP*-violating if one assumes *CPT* invariance). The current limit is of order 0.03 [45]. A new search for this effect is planned at KEK [46]. The Standard Model predictions for these asymmetries are of order 10^{-5}.

3.3 CP violation in the Charm Sector

Because the GIM cancellations in the d, s, b sector are more exact than in the u, c, t sector both mixing and penguin effects are expected to be small in the charm mesons. Thus Standard Model predictions for mixing of the neutral D mesons are generally very low, 10^{-8} or less. Predictions for direct *CP* violation in D decays are somewhat more encouraging. Particle and antiparticle partial decay rates to charge conjugate final states can differ only if (at least) two amplitudes with different weak phases and different strong phases lead to the same final state. In the Standard Model this occurs only for Cabibbo-suppressed decays. Furthermore decay modes for which one anticipates that at least two amplitudes contribute to the same final state are generally quite difficult to pick out experimentally. For decay modes with branching ratios on the order of 0.1% the expected asymmetries are at most a few times 0.1%, assuming the Kobayashi-Maskawa phase is fairly large ($\eta > 0.3$). Thus neither mixing nor direct *CP* violations in D decays are expected to be observable, at the level predicted by the Standard Model, in foreseeable experiments. However new physics from beyond the Standard Model may give much larger effects and hence these searches should be undertaken in the same spirit as searches for rare or forbidden decays [47].

A $5\,\sigma$ signal for direct *CP* violation at the level of the Standard Model predictions would require a parent meson sample of at least 10^{10} events. While this is nominally within the reach of a dedicated fixed target experiment at Fermilab, triggering and reconstruction inefficiencies make it unlikely that measurements can really be made with this precision. A dedicated tau-charm factory would produce of order 10^8 charmed mesons per year at design luminosity, of which 15% might be reconstructed. A B Factory is likely to produce a similar number of reconstructed D's. Thus, as stated above, it will be difficult to observe an effect at the level of the Standard Model prediction, but searches for unexpectedly large effects should be pursued.

Physics beyond the Standard Model in general does not predict direct *CP* violation greater than a fraction of a percent (with the possible exception of models with with a fourth non-sequential generation of quarks). However some models predict significant changes in the mixing mechanism and hence greatly enhanced indirect *CP* violation in D^0 decays. For example a 5% asymmetry in a doubly Cabibbo-suppressed decay rate would correspond to a new amplitude almost a factor of 100 less than the dominant spectator decay amplitudes of the Standard Model. Assuming that new physics produces amplitudes $\propto (g'/M_X)^2$, where g' is a coupling strength and M_X is the mass scale of the new physics, such a search for direct *CP* violation would be probing conventional coupling strength physics at the TeV scale.

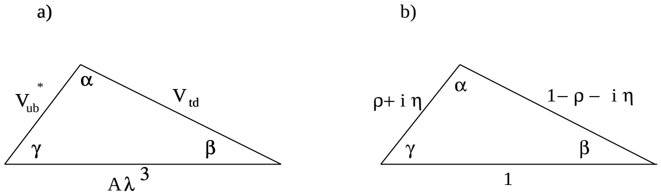

Figure 1: The unitarity triangle, (a) the relation obeyed by the CKM elements; (b) the relation obeyed by (CKM elements)/Aλ^3

3.4 CP Violation in B decays

The B system provides a rich laboratory for the study of *CP* violation [48]. The neutral B mesons are expected to exhibit indirect *CP* violation, like the neutral K's. However in the B case there are a number of possible *CP* eigenstates that can be studied and the relationships between the measured asymmetries in these different channels will provide an excellent way to discover whether the pattern of *CP* violation is as expected in the Standard Model or quite different. For a review of the theoretical predictions for *CP* violation in B decays in the Standard Model and beyond see [49] and references therein.

Unitarity of the CKM matrix gives, among others, the relationship

$$V_{tb}^* V_{td} + V_{cb}^* V_{cd} + V_{ub}^* V_{ud} = 0, \tag{18}$$

which can be displayed as a triangle in the complex plane, as shown in Figure 1a. The base of this triangle can be rescaled to be of unit length, as shown in Figure 2b.

Constraints on the unitarity triangle come from the value of ϵ in K_L^0 decays, from the measured rate for $B_d^0 - \bar{B}_d^0$ mixing, and from the determination of $|V_{ub}|/|V_{cb}|$. At present there are significant theoretical and experimental uncertainties in the relationship between these measured quantities and the parameters of the underlying theory. However, the trend of steadily improving lattice calculations of quantities such as the f_B and B_B parameters should help this situation. The values of the parameters used here are [1,50,51,52]

$$\begin{array}{ll} x_d = 0.65 \pm 0.08\,, & f_B\sqrt{B_B} = 200 \pm 40\,\mathrm{MeV}\,, \\ |\epsilon| = (2.259 \pm 0.018) \times 10^{-3}\,, & B_K = 0.75 \pm 0.05\,, \\ |V_{ub}|/|V_{cb}| = 0.076 \pm 0.026\,, & |V_{cb}| = 0.040 \pm 0.003\,, \\ \tau_{B^0} = 1.50 \pm 0.11\,\mathrm{ps}\,, & \end{array} \tag{19}$$

and with the value of the running top-quark mass, $m_t(m_t)$ corresponding to the physical range claimed [53] by CDF, $m_{t_{phys}} = 174 \pm 16$ GeV. The status of the constraints on the unitarity triangle either from existing measurements or theoretical estimates of these parameters, is shown in Figure 2. This result translates into allowed ranges for the three angles α, β and γ of the unitarity triangle of

$$\begin{aligned} -0.89 \leq & \ \sin 2\alpha & \leq 1.00\,, \\ 0.18 \leq & \ \sin 2\beta & \leq 0.81\,, \\ -1.00 \leq & \ \sin 2\gamma & \leq 1.00\,. \end{aligned} \qquad (20)$$

To learn more about the nature of *CP* violation from the study of B decays, a systematic study of many channels is required. Simply observing a single *CP*-violating effect in the most accessible channel, while interesting, will not do enough to determine the source of *CP*-violation in particle theories. One must make a number of measurements with sufficient precision, and carry out the theoretical calculations with sufficient accuracy, so that one would be sensitive to sources of *CP* violation other than the CKM phase. In practice, what this means is overdetermining the CKM matrix, measuring the magnitudes of the elements, and the phases between elements, via *CP* violation measurements in a variety of B-decay channels, and seeing if it all fits together. Fortunately nature offers us the opportunity to do just that.

CP violation measurements are thus an essential part of a larger effort to look for new physics by overdetermining the CKM matrix. If the overdetermined CKM matrix elements were found to be inconsistent, with different values obtained from different ways of fixing the quantities, that would imply physics from beyond the Standard Model. This additional physics could in itself be *CP*-conserving, for example an additional *CP*-conserving contribution to $B^0 - \bar{B}^0$ mixing would destroy the predicted relationship between the phase of the mixing amplitude and the phases of CKM matrix and hence lead to contradictory results for the value of such elements when treated as if the mixing has only Standard Model sources. Alternately there could be additional types of *CP*-violating phase introduced from additional couplings in the extended model.

Tables 2 and 3 list the channels for B decay for which *CP*-violating asymmetries arising from the interference of mixed and unmixed decays can occur, and the Standard Model prediction for the relationship of the tree decay amplitude weak phase, ϕ_D ($\overline{A}/A = e^{-2i\phi_D}$) and the relative phase of the two terms in the heavy neutral B mass eigenstate, ϕ_M ($q/p = e^{-2i\phi_M}$). These govern the expected asymmetries in the Standard Model.

Table 2: *CP* Modes for B_d Decays and Standard Model Asymmetry Predictions.

Quark process	B_d Mode	$\phi_M - \phi_D$
$b \to c\bar{c}s$	$J/\psi K_S^0$	β
$b \to c\bar{c}s$	$J/\psi K^{0*}$	β
$b \to c\bar{c}d$	D^+D^-	β
$b \to c\bar{c}d$	$D^{+*}D^{-*}$	β
$b \to u\bar{u}d, d\bar{d}d$	$\pi^+\pi^-$	α
$b \to u\bar{u}d, d\bar{d}d$	$\rho^0\pi^0$	α

Table 3: *CP* Modes for B_s Decays and Standard Model Asymmetry Predictions.

Quark process	B_s Mode	$\phi_M - \phi_D$
$b \to c\bar{c}s$	$J/\psi\phi$	0
$b \to c\bar{c}d$	$J/\psi K_S^0$	0
$b \to s\bar{s}s$	$\phi\phi$	0
$b \to u\bar{u}d, d\bar{d}d$	$\rho^0 K_S^0$	γ
$b \to s\bar{s}d$	ϕK_S^0	β

In compiling these tables various simplifying approximations have been made[54], for example that a single weak decay amplitude dominates the decay. The contribution of penguin processes could invalidate this assumption in some channels, and further analysis and cross-checks are needed, to determine whether such contributions are large. Isospin analysis of related channels can be used to remove possible QCD penguin contributions [55], but Z-penguin contributions cannot be removed in this way and can introduce significant effects in certain cases [56].

The channels for B_s which the Standard Model predicts zero asymmetry because of a cancellation of the decay weak phase with the mixing amplitude weak phase are interesting. In models with very different mixing mechanisms these channels would be expected to have asymmetries comparable to those in other channels.

All of the above effects are of the same type as the already observed *CP* violation in K decays, that is they occur because of interference between decay with and without mixing in B^0 decays to flavor-neutral channels. In addition one expects direct *CP* violation at the few percent level in B decays in the Standard Model, larger in channels with Cabibbo-suppressed tree contributions. These effects can most readily be searched for in the decays of charged B's. Searches for asymmetries in any charged B decay channels are thus of interest and should be pursued. The largest asymmetries are expected in those channels where tree and penguin diagrams give comparable strength contributions because of the Cabibbo suppression of the tree amplitude ($b \to u\bar{u}s$ *e.g,* $B^+ \to K^{*+}\rho^0$) [57]. While the magnitude of the expected asymmetry depends on strong phase shifts and

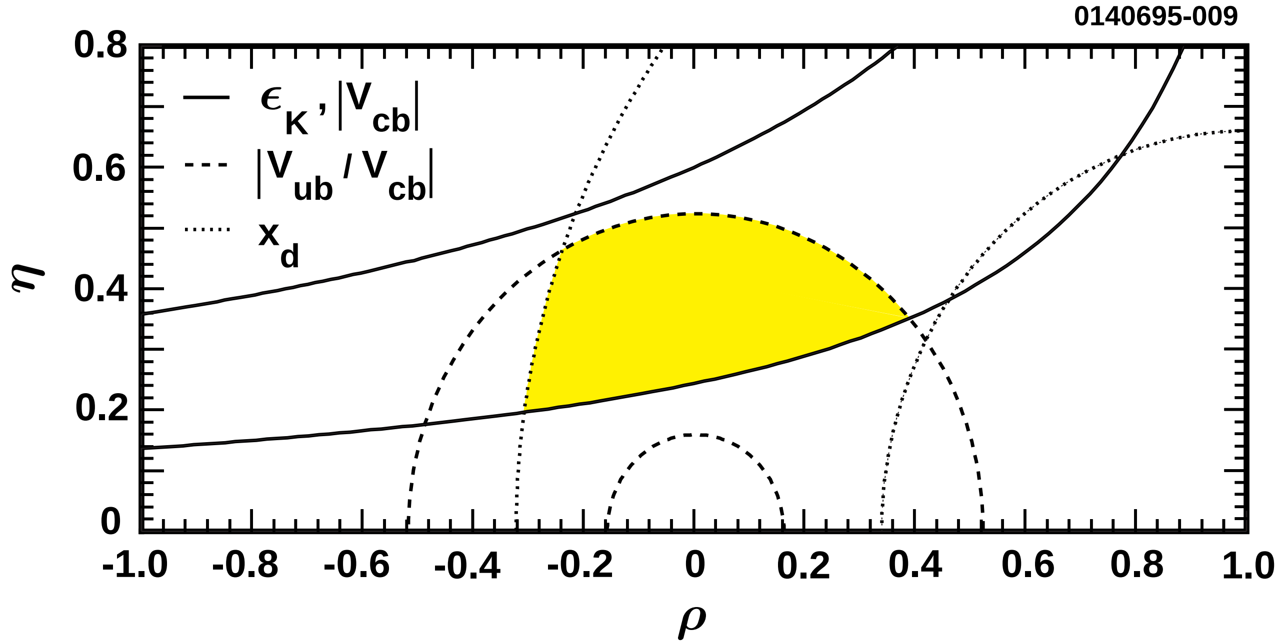

Figure 2: Constraints on the unitarity triangle.

cannot be reliably predicted, the observation of such an asymmetry would be a clear demonstration of the existence of direct *CP* violation.

Experiments which can study many of the channels above will be a feature of the next generation of *B* physics. These are discussed further in the section on facilities.

3.5 Tests of CP Invariance in Tau Decays

CP violation is not expected in the leptonic sector, in the context of the Standard Model. If, however, neutrinos have mass and mix in analogy with the CKM mechanism in the quark sector, *CP* violation can occur in tau decays. Since we know that any neutrino masses are much smaller than quark masses, this source of *CP* violation is already well below our ability to detect in foreseeable experiments. Thus, if *CP* violation is indeed observed in tau decays, it would be an exciting signal for an unanticipated source beyond the Standard Model.

Both the total cross section and differential rate for $e^+e^- \rightarrow \tau^+\tau^-$ are sensitive to *CP*-violating form-factors. For unpolarized beams, only two form factors contribute to *CP*-odd correlation functions in tau-pair production: the electric dipole moment of the τ, $d_\tau(q^2)$, and the weak dipole moment $d^w_\tau(q^2)$. The LEP experiments collect data near the peak of the Z and are sensitive to a weak dipole moment, at $q^2 = m_Z^2$. A non-zero value of $d^w_\tau(q^2)$ would contribute to the width , $(Z \rightarrow \tau^+\tau^-)$ and would introduce *CP*-odd correlations of the momenta of the τ^+ and τ^- decay products [58]. These correlations have been searched for by the ALEPH and OPAL collaborations by forming *CP*-odd triple products from the momenta of the decay products of the two taus in the event. They obtain results consistent with zero *CP*-violating correlations. Combined with the measurements of , $(Z \rightarrow \tau^+\tau^-)$ in comparison with Standard Model predictions a limit of $|d^w_\tau| < 2.9 \times 10^{-17}$ $e \cdot$cm at 95% C.L. is obtained. Improvements in these limits, as well as tests below the Z where $d_\tau(q^2)$ is probed, can be expected in the next decade. The remote possibility that a non-zero dipole moment can be seen remains an enticing possibility, well worth the effort.

3.6 Summary

There are clearly many areas of *CP* violation physics to study. Standard Model predictions relate heavy flavor *CP* violating effects to the magnitudes of CKM parameters through the unitarity of the three-generation theory. Models beyond the Standard Model can violate these relationships and at the same time may introduce significant contributions in channels that are forbidden or loop-suppressed in the Standard Model. Thus the multiple avenues of precision rare decay searches in *K* physics, multiple CKM parameter determinations via different channels, and systematic study of *CP* Violations, both direct and indirect, in as many channels as possible should all be explored as possible low-energy windows to physics beyond the Standard Model.

4 Rare and Forbidden Decays

4.1 *Introduction*

The search for processes that are either forbidden or very rare in the Standard Model is a powerful technique for testing the model as well as for obtaining important constraints on physics beyond the Standard Model. The search for forbidden processes, exemplified by the search for decays violating lepton number, holds forth the possibility of revealing a "smoking gun" of evidence that *there is* physics beyond the Standard Model. The search, and finally, the measurement of partial rates for very rare decays offers the opportunity to test predictions of the Standard Model at the quantum loop level where significant deviations can again point to the presence of new physics [59,60,61].

4.2 *Lepton Flavor Violation*

The search for decays involving the violation of lepton flavor conservation gets to the heart of the matter in that these searches can hopefully shed light on the *generation* puzzle posed by the Standard Model. The replication of the fundamental fermions to include three *families* of quarks and leptons is accommodated but not explained within the Standard Model. Although mixing among the quark flavors in the charged–current weak interactions occurs, governed by the unitary Cabibbo–Kobayashi–Maskawa matrix, mixing of the lepton families does not. The conservation of lepton family number, separately for e, μ and τ, must be invoked to explain the absence of decays such as $\mu \rightarrow e\gamma$, etc. At face value, without any extension to the Standard Model, the conservation of lepton family number would require an exact global symmetry, or an unbroken local gauge symmetry with unobserved massless gauge bosons mediating long–range forces.

Flavor–changing transitions resulting in lepton number violating decays are present at some level in many extensions of the Standard Model. In some models, for example those involving a (broken) horizontal gauge symmetry, lepton flavor violation is quite natural. Some of the branching ratio limits that have been obtained experimentally on lepton flavor violating processes are given in Table 4.

Many of these limits (especially from muons and kaons) are stringent enough to place important constraints on model building. The relative importance of these constraints, and those that can be obtained in the future from continued searches depends on the nature of the new physics. And the interplay of limits obtained in several processes is often required to confront the plethora of conceivable extensions to the Standard Model (*e.g.*, technicolor and its extensions, left–right symmetric models, models with composite quarks and/or leptons an extended Higgs sector, supersymmetry, leptoquarks, etc.) [62,63].

Table 4: Limits on Lepton Number Violating Processes

Process	Upper Limit 90% CL	Laboratory
$\mu \rightarrow e\gamma$	4.9×10^{-11}	LAMPF
$\mu \rightarrow eee$	1.0×10^{-12}	PSI
$\mu N \rightarrow eN$	4.3×10^{-12}†	PSI
$\pi^0 \rightarrow \mu e$	1.7×10^{-8}	FNAL
$K_L^0 \rightarrow \mu e$	3.3×10^{-11}	BNL
$K^+ \rightarrow \pi^+ \mu^+ e^-$	2.1×10^{-10}	BNL
$K_L^0 \rightarrow \pi^0 \mu^+ e^-$	3.5×10^{-9}	FNAL
$\tau \rightarrow \mu\gamma$	4.2×10^{-6}	CESR
$\tau \rightarrow eee$	3.3×10^{-6}	CESR
$\tau \rightarrow \mu ee$	3.4×10^{-6}	CESR
$\tau \rightarrow \mu\mu e$	3.6×10^{-6}	CESR
$\tau \rightarrow \mu\mu\mu$	4.3×10^{-6}	CESR
$D^0 \rightarrow \mu e$	1.0×10^{-4}	DESY
$B^0 \rightarrow \mu e$	5.9×10^{-6}	CESR
$B^0 \rightarrow \tau\mu$	8.3×10^{-4}	CESR
$B^0 \rightarrow \tau e$	5.3×10^{-4}	CESR
$B^0 \rightarrow K^{*0} \mu e$	2.7×10^{-5}	CESR
$B^+ \rightarrow K^+ \mu e$	1.2×10^{-5}	CESR

†This is a limit on conversions/captures

The decay $K_L^0 \rightarrow \mu e$ serves as a good illustration of the importance of conducting the search for new physics over a broad range of processes, as well as a chance to point out the sensitivity of the search for rare decays to physics at high mass scales. The required $s\bar{d} \rightarrow \mu^- e^+$ transition could proceed via a tree–level exchange of a leptoquark that coupled s quarks to muons and d quarks to electrons; such a interaction would not contribute to purely leptonic processes ($\mu \rightarrow e\gamma$) or to the $K_L^0 - K_S^0$ mass difference ($\Delta m_K = 3.5 \times 10^{-15}$ GeV, otherwise the most important constraint on flavor–changing neutral current interactions.) Assuming the new interaction has a $V - A$ form, the $K_L^0 \rightarrow \mu e$ decay rate can be compared directly with the familar decay $K^+ \rightarrow \mu^+ \nu_\mu$. If the leptoquark–fermion vertices carry the weak interaction coupling, this comparison leads to the result [61]:

$$BR(K_L^0 \rightarrow \mu e) = 10^{-12} \times (\frac{220\text{TeV}}{M_{LQ}})^4 \qquad (21)$$

where M_{LQ} is the mass of the leptoquark. With these assumptions, the current experimental limit translates into a lower bound on M_{LQ} of 90 TeV, a mass scale well beyond the reach of direct production with present or planned accelerators. However, since the branching fraction depends on the fourth power of M_{LQ}. substantial progress in limiting M_{LQ} will be difficult. Similar arguments can be made for the decays $K^+ \to \pi^+\mu^+e^-$ and $K_L^0 \to \pi^0\mu^+e^-$. However, it is important to note that the searches for these two decay modes are complementary given that $K_L^0 \to \mu e$ must proceed through axial–vector or pseudoscalar interaction and $\pi\mu^+e^-$ modes require a vector or scalar interaction.

Given the wealth of possibilities for new physics, it is important to cast a wide net, keeping in mind that generic constraints implied by limits on one process may be evaded in a particular class of models and lead to observable rates for another process. The impressive limits set for lepton flavor violation with muons and K mesons do not necessarily exclude the possibility of observable rates for lepton flavor violating decays of tau leptons, mesons or baryons containing charm or beauty, or even of the top quark. Several models for new physics include fermion mass–dependent (Higgs–like) couplings that enhance the rate for various τ, D, and B decays relative to the expectations for those of muons and K mesons. Also the space–time nature of the new interaction currents (S, P, V, A, T) plays a crucial role in determining the relative rates for specific decay modes (*e.g.*, whether $B \to \mu e$ suffers a helicity suppression with respect to $B \to \pi\mu e$ or $K\mu e$).

It should be noted that in perhaps the simplest extension of the Standard Model, where neutrinos are given a mass and neutrino oscillations are allowed, lepton flavor violating decays can occur, albeit at rates well below the limits already placed: branching ratios of order 10^{-20} would be expected for $\mu \to e\gamma$ and of order 10^{-15} for $K_L^0 \to \mu e$ assuming neutrino masses and mixing at the current experimental limit (see Working Group report on neutrinos). A branching ratio of 10^{-16} could be expected for $\mu A \to eA$.

4.3 Loop Induced Rare Decays

In the Standard Model, flavor–changing neutral currents (FCNC) are forbidden to first order and strongly suppressed at higher orders by the Glashow–Illiopoulos–Maiani (GIM) mechanism [64]. The measurement of GIM suppressed decays offers an opportunity to study higher–order weak interactions, particularly the contributions of the top quark in loop processes and the CKM couplings V_{td} and V_{ts}. The highly suppressed nature of the FCNC decays also offers a potential window on new physics. In what follows several specific classes of suppressed decay modes are discussed.

4.3.1 $K, D, B \to l^+l^-$

The decay $K_L^0 \to \mu^+\mu^-$ is probably the most famous of the GIM suppressed decays. The suppression of its rate relative to $K^+ \to \mu^+\nu_\mu$ was a serious problem for the early Standard Model, and required the invention of the GIM mechanism and the existence of the charm quark. With GIM suppression the decay rate is expected to be dominated by contributions from a two–photon intermediate state, with the contributions from real photons resulting in a “unitarity bound” of 6.8×10^{-9} for the $K_L^0 \to \mu^+\mu^-$ branching ratio [61]. Recent efforts at BNL and KEK have yielded a measurement of the decay rate to better than 10% and the result is consistent with the “unitarity bound.” Further improvements (perhaps approaching a 1% measurement) are expected. Further progress in extracting the contributions of the higher–order weak interactions and contributions from the top quark will require understanding the contributions from the two–photon intermediate state with virtual photons. If the uncertanties from these contributions can be eliminated, the $K_L^0 \to \mu^+\mu^-$ process can provide a measurement of the CKM parameter ρ. Progress on this front has been made recently with measurements at BNL, CERN, KEK and FNAL on the decays $K_L^0 \to \gamma e^+e^-$, $K_L^0 \to e^+e^-e^+e^-$ and $K_L^0 \to \gamma\mu^+\mu^-$ and improved measurements are expected in the future.

The decay $K_L^0 \to e^+e^-$ shares much of the same physics with the decay $K_L^0 \to \mu^+\mu^-$, but contributions from the Standard Model are suppressed by a factor proportional to m_e^2/m_μ^2. The recent limit established at BNL, $\mathrm{BR}(K_L^0 \to e^+e^-) < 4.1 \times 10^{-11}$ [65], is an order of magnitude above the “unitary bound” for this mode of 3×10^{-12}. This still leaves room for contributions from physics beyond the Standard Model, particularly from a pseudoscalar interaction that would avoid the helicity suppression.

The decays of neutral B and D mesons to $\mu^+\mu^-$ final states also offer a means to test the predictions of the Standard Model for one–loop decays. Figure 3 illustrates loop diagrams contributing to the process $B \to \mu^+\mu^-$. The possibility of observing $D \to \mu^+\mu^-$ seems remote due to the presence of helicity suppression, small CKM elements and the absence of the heavy top quark in the one–loop diagrams, particularly remembering that normal D decays are not even Cabibbo suppressed. New physics could of course evade these constraints. With the B meson decays, especially $B_s \to \mu^+\mu^-$ the situation is more favorable. In this case the top quark loop effects are more important for $b \to s$ than $s \to d$ transitions (relevant to K decays), and $B_s \to \mu^+\mu^-$ is expected to be dominated by the higher–order weak interactions rather than long–distance intermediate $\gamma\gamma$ states. The expected branching ratio in the Standard Model is about 10^{-9} [66].

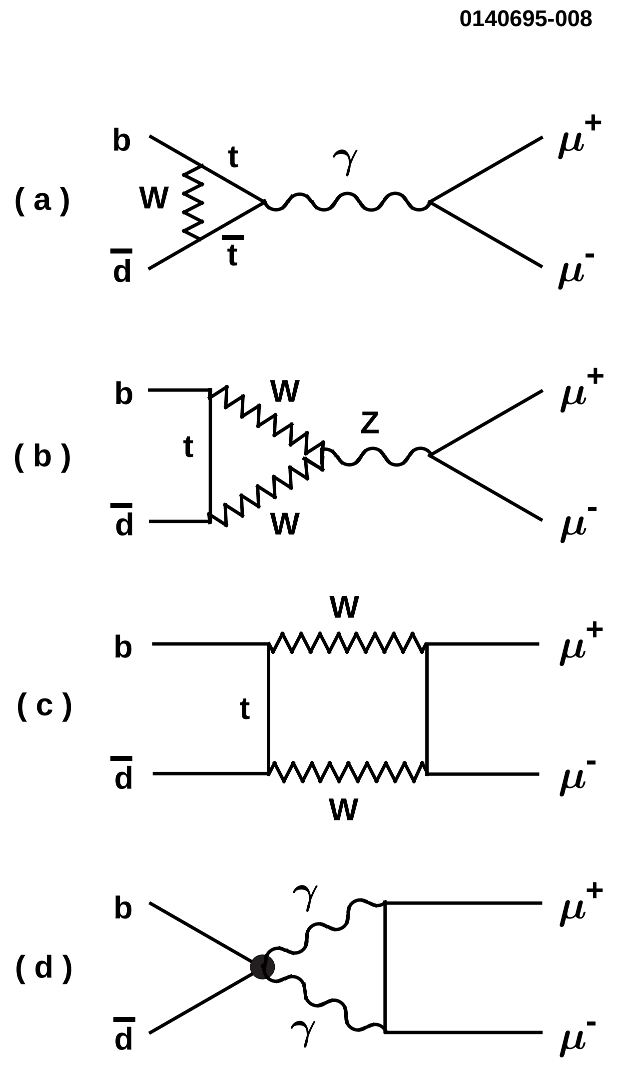

Figure 3: Diagrams contributing to the rare decays $B^0 \to \mu^+\mu^-$ (or $K^0 \to \mu^+\mu^-$ with $b \leftrightarrow s$.)

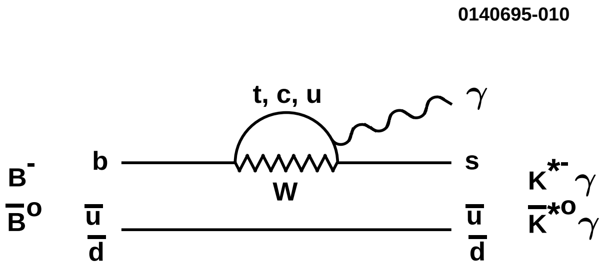

Figure 4: Penquin decay of a B meson to $K^*\gamma$.

4.3.2 Penguin Decays: $K \to \pi l\bar{l}$, $b \to s\gamma$, $b \to sl\bar{l}$.

This class of decays receives contributions from penguin diagrams as well as from the W box diagrams at the one–loop level. Also the helicity suppression of the previously discussed decays is avoided. Correspondingly, rates expected in the Standard Model are enhanced.

The observation [67] of the decay $B \to K^*(892)\gamma$, reported by the CLEO experiment, is the first direct evidence for the penguin diagram. This decay is described by the electromagnetic transition $b \to s\gamma$, which is a $b \to s$ penguin loop accompanied by the radiation of a photon from either the loop, or the initial or final state quarks. (Figure 4 illustrates the penguin diagram for $B \to K^*\gamma$.)

Unfortunately, due to the theoretical uncertainties in translating the branching ratio for the exclusive process into a rate for the parton level process, this result cannot be used to quantitatively test the Standard Model. Recently, CLEO has succeeded in measuring the rate for the inclusive process $b \to s\gamma$ [68]. The measured rate is consistent with the Standard Model and constrains many extensions of the Standard Model. These include charged Higgs bosons below about 250 GeV anomalous $W - W - \gamma$ couplings, SUSY Higgs, and so on [69]. Theoretical uncertainties for the Standard Model rate are currently ±30%, but could be reduced considerably with a full next-to-leading-log calculation [70]. This should be given high priority. If these calculations are done, improved experimental precision will provide additional constraints on new physics (or see evidence of it). As noted in other sections, indirect constraints on rare processes can often provide more stringent constraints than direct searches at high-energy colliders.

The process $b \to sl^+l^-$ is mediated at the parton level by the process $b \to s\gamma^*$ or $b \to sZ^*$ where the virtual particle decays to lepton pairs (here γ^*,Z^* indicates a virtual photon or Z). Exclusive final states such as $B \to K^*l^+l^-$ are expected. Unlike $b \to s\gamma$ processes, there are no significant QCD corrections in this case [71]. Heavy neutral particles that occur in extensions of the Standard Model may enhance the rate for this type of process.

Unfortunately, significant long distance contributions are also expected to give rise to the same final state. These may be separated with high statistics observations of the detailed kinematic properties in the decay.

The decay $K^+ \to \pi^+ \nu\bar{\nu}$ is expected to occur at a branching fraction of about 10^{-10}; the current experimental limit from BNL is 3×10^{-9}. As discussed in the section on CKM parameters, the decay $K^+ \to \pi^+ \nu\bar{\nu}$ offers a relatively clean way of measuring $\mid V_{td} \mid$ as the theoretical uncertainties can be controlled to 10% or better. A byproduct of the search for $K^+ \to \pi^+ \nu\bar{\nu}$ are limits placed on the process $K^+ \to \pi^+ X^0$. Here X^0 is an essentially invisible particle such as an axion, familon, or hyperphoton.

The decays $K_L^0 \to \pi^0 e^+ e^-$ and $K_L^0 \to \pi^0 \nu\bar{\nu}$ have been discussed in the section on *CP* violation, by virtue of their sensitivity to direct *CP* violation in the Standard Model. The current branching ratio sensitivities achieved (10^{-9} for $K_L^0 \to \pi^0 e^+ e^-$) allow a considerable window of opportunity for non–Standard Model (*CP* violating contributions) above the predicted Standard Model ratio of $O(10^{-12})$.

5 Strong Interaction Effects in Heavy Flavor Physics

5.1 Theoretical Background

Studies of the masses, static properties, and decays of hadrons containing heavy quarks have provided a fertile testing ground for our understanding of QCD dynamics. In addition, to extract the electroweak parameters for quarks from the observations of the mixing and decays of hadrons, the nonperturbative effects of QCD cannot be ignored. In particular, the determinations of the quark masses and CKM parameters from the weak decays of K, D, and B mesons have significant theoretical components to the present errors. Improving these determinations will require both experimental and theoretical efforts.

The principal theoretical tools available to help disentangle these nonperturbative QCD effects are:

- Lattice gauge theory. This is the only existing technique which allows the systematic study of all aspects of QCD and will be a critical ingredient in the theoretical effort to understand heavy flavor physics [72]. A significant present limitation of the lattice approach is that calculations including internal quark loops require more computing resources than now exist. If the rate of improvement in numerical methods and computing cost remains the same, this situation should improve dramatically over the next 5-10 years.
- QCD Sum Rules. This approach exploits the duality in QCD between the description in terms of physical states (at low energy) and elementary quark and gluon excitations (at high energy). Such models for the dynamics can shed considerable light on the properties of heavy systems.
- Heavy Quark Effective Theory(HQET). The dynamics of QCD simplifies as $m_Q \to \infty$. In this limit the dynamics becomes independent of the spin and flavor of the heavy quark [11]. These heavy quark symmetries (HQS) can be exploited to relate masses, decay rates, form factors, and many other physical quantities within various heavy flavor systems.
- Chiral Perturbation Theory. The effective lagrangian for interactions involving pions and kaons is constrained by chiral symmetry [73]. Quark masses explicitly break this symmetry and can be treated as correction terms for π and K interactions.

5.2 Spectroscopy and Strong Decays

5.2.1 Heavy-Heavy systems

Heavy quark systems allow the study of the strong dynamics of QCD in simple limits. The most familiar heavy quark systems are the $Q\bar{Q}$ mesons. As the mass of the quark, m_Q, becomes much heavier than the QCD scale ($\Lambda_{\rm QCD}$), the dynamics becomes nonrelativistic. The ratio of the typical momentum transfer (between the heavy quark and antiquark) to the heavy quark mass, m_Q, remains small as $m_Q \to \infty$. Hence a systematic expansion in powers of this ratio (the relative velocity $\vec{v}$) can be employed. The quarks and antiquarks move in an effective potential $V(R)$ generated by the QCD interactions. Nonrelativistic potential models of the $(\bar{c}c)$ and $(\bar{b}b)$ family of resonances(*i.e.*, the J/ψ and Υ resonances) have been very successful [74]. Relativistic corrections and hadronic transition rates have all been extensively studied. Existing lattice calculations agree well with the phenomenologically determined potential $V(R)$. Lattice techniques are now being used to directly calculate the masses and splittings in the $c\bar{c}$ and $b\bar{b}$ systems and extract the heavy quark mass.

The B_c meson spectrum would be a particularly interesting $Q\bar{Q}$ system to study because of its unequal heavy quark masses. Some of the B_c decay modes are experimentally striking (such as $B_c \to J/\psi\pi^-$ and $J/\psi a_1^-$). Such modes make the study of B_c mesons possible at a high luminosity hadron collider.

5.2.2 Heavy-Light Systems

The top quark is so heavy that it decays weakly before hadronic states have time to fully form; for the remaining heavy quarks, however, the weak interactions can be treated as a small perturbation. For hadrons that contain a single heavy quark, the QCD interactions again takes a simple form as $m_Q \to \infty$. The momentum transfers between the heavy quark and the rest of the system are typically of the scale of the light quark masses and $\Lambda_{\rm QCD}$ and thus remains bounded as the heavy quark mass goes to infinity. Hence in the $m_Q \to \infty$ limit, the heavy quark is on shell and at rest relative to the hadron and the QCD dynamics becomes independent of m_Q. All heavy quark mass dependence of the bound state can be extracted analytically to produce an effective action (HQET)for a static quark and the remaining light degrees of freedom. This effective action makes transparent symmetry and scaling relations between heavy-light systems which differ by heavy quark spin or flavor [75]. Furthermore, for finite heavy quark masses, the effective action can be improved order by order in $1/m_Q$, and QCD corrections calculated systematically as a expansion in $\alpha(m_Q)$.

These theoretical developments have immediate physical applications for B physics. Since the b quark mass is significantly heavier than the other mass scales (the QCD scale and the light quarks masses) which enter into the dynamics of B hadrons, it is a good approximation to treat the b quark in $m_Q \to \infty$ limit within B hadrons. It is also fruitful to consider the charm mesons and baryons as heavy-light systems, although corrections are larger in this case.

The Heavy Quark Symmetry (HQS) predicts that the leading corrections to the spectrum are inversely proportional to the heavy quark mass. This relates D meson masses to B meson masses, and predicts an interesting spectra of B^{**} and D^{**} mesons. Furthermore the decays of these excited heavy-light mesons satisfy certain symmetry relations in $m_Q \to \infty$ limit.

One application of the existence of such excited B states has been suggested. If significant numbers of B mesons are produced through one or more narrow excited states, then the strong decay $B^{**\pm} \to B^{(*)0}\pi^{\pm}$ tags the neutral B mesons as $(\bar{b}d)$ or $(\bar{d}b)$, respectively [76]. This would improve the situation for CP violation studies in hadron machines.

The spectroscopy of heavy baryons, particularly baryons with two heavy quarks, can also provide important additional insight into the dynamics of QCD.

5.3 Weak Leptonic and Semileptonic Decays

A heavy quark decays via the weak charged current into its electroweak partners (with couplings determined by appropriate CKM element) and a virtual W. The virtual W, in turn, decays to either a quark-antiquark pair or into leptons. The quark-antiquark pair decay is enhanced in rate relative to the $l\nu$ decay by the color factor.

To date no evidence for lowest-order flavor- changing neutral decay currents has been observed. This puts stringent constraints on models of physics beyond the standard model. However the limits for heavy flavors are much less stringent than those on the $s \to d$ transition that come from the small $K_L^0 - K_S^0$ mass difference.

5.3.1 Leptonic Decays

The fully leptonic decay probability for a pseudoscalar meson, $P^+ = (q'\bar{q})$, to a charged lepton and neutrino is described by

$$\Gamma(P^+ \to l^+\nu_l) = \frac{G_F^2}{8\pi} f_P^2 \; m_P \; m_l^2 |V_{q'q}|^2 (1 - \frac{m_l^2}{m_P^2})^2. \quad (22)$$

The pseudoscalar decay constants f_P of the heavy-light mesons are of interest for the study of mixing and CP violation for **both** the charm and beauty sector. In the large m_Q limit, HQET requires $\sqrt{M_P} f_P$ to be independent of the heavy quark mass up to calculable perturbative corrections [77]. For finite heavy quark mass the corrections are $O(1/m_Q)$.

No data exists for f_D, but during the past year two results on f_{D_s} were reported [78]. One technique uses emulsion to measure the direction of the D_s^+ and then measures the $p_{T\mu}$ of the muon relative to the D_s^+ direction. The second technique uses the decay chain $\mathrm{D}_s^{*+} \to \gamma \mathrm{D}_s^+$ and examines $\mu\gamma$ correlations. The results of both techniques have large errors and only agree at the one standard deviation level. Over the next several years the value of f_{D_s} will improve. A good measurement of f_D and especially f_B will be difficult, forcing us to rely on theoretical calculations.

Lattice calculations using a variety of methods allow the determination of decay constants in the heavy quark limit as well as directly for the strange, charm, and beauty mesons. The present theoretical range for f_B [79], from 150-200 MeV, implies factor of 2 variation in B mixing. Ratios of decay constants are better determined. Significant improvements in the accuracy of the lattice calculations of f_B and f_D can be expected in the next few years.

5.3.2 Semileptonic Decays

After the fully leptonic decays, the semileptonic decays are the next simplest theoretically. Both decays to inclusive and exclusive hadronic final states are theoretically important. For example, from B meson inclusive measurements, the ratio of CKM matrix elements $|V_{ub}|/|V_{cb}|$ can be determined. There is some dependence on the QCD strong dynamics and theoretical model differences account for a sizable component of the total uncertainty in this measurement. To reduce these theoretical uncertainties we need to understand the dynamics of $b \to u$ transitions near the lepton endpoint for the $b \to c$ transitions.

At present, there is even disagreement between theory and experiment in the B meson system on the total semileptonic branching ratio. The measured value is $(10.35 \pm 0.17 \pm 0.35)\%$ from a model independent dilepton analysis and comparable but more precise rates are obtained from the analysis of the single lepton spectrum [80]. These measurements are significantly smaller than the expected theoretical lower bound $BR_{sl} > 12.5\%$. Whether the resolution of this discrepancy is due to an unexpected enhancement in the non-leptonic B partial rates or other large corrections to the theoretical expectation is presently unresolved.

Semileptonic decays to exclusive single hadron final states are under better theoretical control but require much larger data samples to fully study. They occur only via the spectator diagram and there are no final state interactions. The hadronic physics enters through a single matrix element which is expressed in terms of form factors. The momentum transfer in the decay is given by $q^2 = M^2(l\nu)$. The heavy-light meson (P) decays are usually separated into pseudoscalar (P') and vector ($P^{*\prime}$) (final hadronic state) decays.

The pseudoscalar decay $P \rightarrow P'l^+\nu$ decay is governed by two form factors called $f_+(q^2)$ and $f_-(q^2)$. Generally the $f_-(q^2)$ term is neglected as it is multiplied by the lepton mass squared.

For the vector decay $P \rightarrow P^{*\prime}l^+\nu$ there are 3 form factors, $\mathrm{A}_1(q^2)$, $\mathrm{V}(q^2)$, and $\mathrm{A}_2(q^2)$ which describe the decay. (Actually there is a fourth, but it appears multiplied by the lepton mass squared, and so is irrelevant experimentally.)

For P' and $P^{*\prime}$ heavy-light mesons, the decay amplitudes take a particularly simple form in the heavy quark limit. All explicit dependence on heavy quark masses vanishes (up to calculable perturbative QCD correction), and only a single form factor, the Isgur-Wise function [11] ξ which is a function of the product of the initial and final hadron four velocities ($v \cdot v'$) remains. The HQET does not determine ξ. Additional form factors appear in order $1/m_Q$.

Thus far the form factors have been measured assuming a pole mass-shape form factor as given in the pseudoscalar decay. The values for $\mathrm{A}_1(0)$ and $\mathrm{V}(0)$ are reasonably well determined while the error on $\mathrm{A}_2(0)$ needs to be reduced. Experiments need to improve statistics in order to gain sensitivity to the shape of the form factors.

The q^2 dependence is usually given as $f_+(q^2) = f_+(0)/(1 - q^2/M^2_{D^*_s})$ although HQET assumes an exponential q^2 dependence.

It is important to measure extremely well the form factors of $D \rightarrow Kl^+\nu$ and $D \rightarrow K^*l^+\nu$ and then relate them to $B \rightarrow \pi l^+\nu$ and $B \rightarrow \rho l^+\nu$. This extrapolation might be accomplished with HQET, quark sum rules, or lattice gauge calculations. If the form factors were understood, then it would be possible to make a solid measurement of $|\mathrm{V}_{ub}|$.

- $D \rightarrow$ Pseudoscalar Decay

In the $D \rightarrow Kl^+\nu$ decay one can learn two pieces of information. First one can fit and determine the pole mass and compare with theoretical predictions. Second, one can assume a pole mass shape and measure the CKM element $|\mathrm{V}_{cs}|$. For the future it will be important to accurately measure the decays of $D \rightarrow Ke\nu$ and $D \rightarrow K\mu\nu$. A comparison of the rates will determine $f_-(q^2)$ and should make possible the best direct measurement of $|\mathrm{V}_{cs}|$.

Similar measurements are needed for the D_s^+ decays and for the Cabibbo suppressed decay $D \rightarrow \pi\mu\nu$. $D \rightarrow \pi\mu\nu$ decay can be compared to $D \rightarrow K\mu\nu$ decay to determine a ratio of $|\mathrm{V}_{cd}|^2/\ |\mathrm{V}_{cs}|^2$.

- $B \rightarrow$ Pseudoscalar Decay

While the decay $B \rightarrow D\ell\nu$ is theoretically much simpler than $B \rightarrow D^*\ell\nu$, from an experimental perspective it is much more difficult. $B \rightarrow D\ell\nu$ has backgrounds from both $B \rightarrow D^*\ell\nu$ (large) and $B \rightarrow D^{**}\ell\nu$ (small), while $B \rightarrow D^*\ell\nu$ has only a small background from $B \rightarrow D^{**}\ell\nu$. Further, D^0 and D^+ have substantial backgrounds under their mass peaks, while D^{*0} and D^{*+}, can be cleanly identified. Consequently, the study of $B \rightarrow D\ell\nu$ has not progressed very far. At such time as its form factor can be measured and compared with those from $B \rightarrow D^*\ell\nu$, it will provide an interesting test of HQET. In the nearer term, a precise measurement of the $B \rightarrow D\ell\nu$ branching ratio is needed, as a step towards determining what fraction of the B semileptonic decay is *not* due to D or D^*. (Unlike the situation on D semileptonic decays, higher resonances and non-resonant states account for a significant piece, approximately $\frac{1}{3}$.)

- $D \rightarrow$ Vector Decay

Comparison of measurements of D and B to $\rho l\nu$ (and $\pi l\nu$) could provide one approach to accurate measurement of $|V_{ub}|$. HQET together with approaches like QCD sum rules or lattice calculation can be used to classify and limit the $1/M_Q$ corrections to this quantity.

For D_s^+ decays there are two experimental measurements of the vector and axial-vector form factors. Both measurements have sufficiently low statistics such that one cannot see whether the D_s^+ form factors are the same as those for the D^+ or not. This test needs to be accurately demonstrated if the extrapolation to the B sector is to be made reliably.

- $B \rightarrow$ Vector Decay

The decay $B \rightarrow D^*l\nu$ has recently been studied by CLEO [81]. They performed a 4-parameter fit, determining the three form factors at the zero-recoil point as well as the slope of the form factors (assumed to be the same for all three). The results are in agreement with the expectations of HQET, but there is need for considerable reduction in experimental error before this can be considered a sensitive test of HQET.

The rate for $B \rightarrow D^*l\nu$ extrapolated to the zero-recoil point provides a relatively model-free determination of $|V_{cb}|$, as discussed in Section 2.1.1.

- Baryon Semileptonic Decays

Charmed and beauty baryon semileptonic decays provide another opportunity to test predictions of HQET. The Λ_c^+ decay should proceed via a Λ or a Λ^* as the isospin must be 0. Thus it is expected that the $l = 0$ decay $\Lambda_c^+ \to \Lambda l \nu$ will dominate the semileptonic decay of the Λ_c^+. The information can be used to relate the decay to the D mesons and thereby determine a branching fraction for $\Lambda_c^+ \to pK^-\pi^+$ [82]. This technique may be an excellent method for determining absolute branching ratios for the Ξ_c^+, Ξ_c^0, and Ω_c^0.

- Other Weak Transitions

There are a number of other weak decays involving the flavor transition of only a single quark in an initial hadron. These processes change the quark isospin by 1/2 or 0 and don't change the charge. Examples of these processes are $b \to s\gamma$ inclusive and exclusive decays (discussed in Section 4.3.2) and Kaon $\Delta I = 1/2$ and $K \to \pi e^+e^-$ amplitudes. The strong dynamics issues in these cases are similar to those encountered in semileptonic decays.

5.4 Weak Nonleptonic Decays

The study of nonleptonic weak decays and mixing of charm and beauty mesons is both rich and complicated. Six types of weak diagrams for a heavy-light meson (P) are possible [83]. These are denoted external spectator, color-suppressed (or internal) spectator, annihilation, exchange, penguin, and mixing. Disentangling the underlying quark processes and their relative strengths from the observed decays and mixing requires a detailed understanding of the strong interaction effects.

The character of hadronic charm decays is qualitatively well-understood in the meson sector. More than 90% of all meson decay channels have been observed. In contrast, for the B mesons approximately 90% of the decay channels are yet to be observed.

The charm meson states are dominated by spectator and color-suppressed spectator diagrams, while in the charm baryon sector the decays appear to be dominated by the exchange mechanism. The annihilation and exchange diagrams are expected to be quite small for meson decays because of helicity suppression. Both penguin and mixing diagrams are suppressed in the charm meson system. For B meson states, the dominant weak decay diagrams are spectator diagrams.

Most theoretical work is based on the assumption of factorization; *i.e.*, the amplitude for the weak decay of a heavy meson can be expressed as the product of two current matrix elements: one current between the initial meson and some of the final state hadrons and the other between the vacuum and the remaining final hadrons [84]. Factorization can be justified in special circumstances. For a two body final state associated with a heavy meson weak decay, this occurs when the quark pair (produced as a color singlet from a virtual W) has high energy (and low Q^2) and hence travels fast enough to leave the interaction region without influencing the second hadron (formed from the remaining quark and the spectator antiquark).

Within the framework of factorization, HQET provides relations between decays. Lattice methods may be able to provide information on two-body final states. Chiral symmetry may also be used to relate decays. However most specific predictions for partial rates are quite model dependent. Here QCD Sum Rule methods provide the best present guide.

There are many topics to investigate even in the charm system. For both the D^0 and the D^+ mesons we know that the decays occur primarily via two body decays. For the D_s^+ meson the situation is not so clear. The weak annihilation process for the D_s^+ has yet to be confirmed [85], with the only evidence for the decay arising from the non-resonant decay of $D_s^+ \to \pi^+\pi^-\pi^+$. The lifetime for the D_s^+ is larger than the D^0 and this again is not expected. The decay of $D^+ \to \phi K^+$ is not only doubly suppressed, but requires an annihilation diagram.

There remains a need to provide a detailed understanding of the strength of the W-exchange process, to provide more information on final-state interactions, to identify SU(3) violations, and to observe penguin decays in charm sector.

Factorization should work better for heavier mesons, but model dependence is still unavoidable. Systematic study of B decays and comparison of B and D decays should help clarify some of the unresolved issues.

5.4.1 Factorization and External Spectator Decays

It is expected that factorization will be more reliable in B meson decays than in the equivalent D meson decays due to the larger characteristic energy transfers and the consequent suppression of final state interactions. For a limited class of decay modes the factorization ansatz has been experimentally confirmed to an accuracy of about 15%.

Factorization is likely a poorer approximation for decays with smaller energy release or larger momentum transfer, q^2. for example in the $B \to D^{(*)}D_s^{(*)}$ decay. Using τ spectral functions, data on $e^+e^- \to n\pi$, and $d, (B \to D^*l\nu)/dq^2$ factorization can be tested using $B \to D^*(n\pi)^-$ decays (n>2) over the wide q^2 range covered by the $(n\pi)^-$ system.

If factorization holds, measurements of hadronic B decays can be compared to theoretical models and used to extract Standard Model parameters. For instance, the CKM matrix element $|V_{ub}|$ could be obtained from $\bar{B}^0 \to \pi^+\pi^-$ or $\bar{B}^0 \to D_s^-\pi^+$. The wave function overlap of the D_s mesons, parametrized in the decay constant f_{D_s} could be extracted from $\bar{B}^0 \to D_s^- D^{*+}$.

Factorization breaks down in the charm sector due to the presence of large final state interactions. The strength of these long distance effects in the B system can be determined by performing an isospin analysis of related decay channels such as $B^- \to D^0\pi^-$, $\bar{B}^0 \to D^0\pi^0$, and $\bar{B}^0 \to D^+\pi^-$ as was done in the past for $D \to K\pi$ and $D \to K^*\pi$ systems [82].

Although factorization has been used to calculate the rates for color suppressed and penguin decays, it is not known whether this is a correct assumption for these diagrams. Experimental verification is needed before model calculations can be trusted.

5.4.2 Inclusive B Decays and the Color Suppressed Amplitude

For Cabibbo favored B decays, the "color suppressed" or internal spectator diagram has the antiquark from the virtual W^- hadronize with the c quark from the b decay. A simple color counting argument then leads to a "color suppressed" rate for this process. So far, the only compelling experimental evidence for this suppression is the observation of inclusive and exclusive $B \to$ charmonium decays. A first order QCD correction involving a hard gluon exchange can defeat this simple color argument. Further information on the size of the color suppressed contribution could be obtained from $\bar{B}^0 \to D^0($ or $D^{*0})X_0$ decays, where X_0 is a neutral meson.

QCD radiative corrections also produce corrections to the weak vertices themselves. In particular, they generate a color octet term in the effective weak Hamiltonian. from the QCD radiative corrections to the weak vertices themselves. There is experimental evidence for the color octet contribution from $B \to \chi_{c2}$ decays.

Many of the color suppressed decay modes, in particular $B^0 \to \psi K^0$ and $B^0 \to \psi K^{*0}$, will be important in *CP* violation studies. *CP* asymmetries in some other channels such as $B \to D^0 K^-$ arise from the interference of a color suppressed amplitude and a $(b \to u)$ spectator amplitude.

By considering decays of B^- (where both external and internal spectator diagrams contribute) the magnitude and sign of the color suppressed amplitude can be determined. By comparing rates for corresponding B^- and $\bar{B}^0$ in the the decay modes $B \to D^{(*)}\pi^-$ and $B \to D^{(*)}\rho^-$ this interference is found to be constructive [86]. Since the evidence for constructive interference is based on a set of decay modes which comprises only 3% of the total width, the generality of this result is unknown. This differs from the pattern observed in hadronic charm decays.

A variety of other decays might shed light on "color suppressed" spectator decays. Hadronic B decays to pairs of baryons as well as $b \to c\bar{c}s$ decays may well provide new windows to understanding the dynamics.

5.4.3 B Lifetimes and W Exchange

If the decays of b flavored hadrons are dominated by the external spectator diagram, and our current explanation of the lifetime differences in the charm sector is correct, then the lifetimes of B mesons and baryons should be the same to corrections of order a few percent. Measurements at LEP and the Tevatron find $\tau_{B^+} \approx \tau_{B^0} \approx \tau_{B_s} \approx 1.6$ ps confirming this expectation. However, the lifetime for the Λ_b baryon is found to be significantly shorter, $\tau_{\Lambda_b} \approx 1.0 - 1.2$ ps [87]. This indicates a larger than expected contribution from internal W exchanges to the Λ_b decay width. In contrast to baryons, W exchange is helicity suppressed in mesons and a significant contribution from multibody final states complicates the search for these decays even further. So far, no evidence for the presence of this mechanism has been found in B meson decay. Measurements of the lifetimes for the other b baryons as well as more precise measurements of the b mesons from LEP and hadron colliders may clarify this issue.

5.4.4 Hadronic Penguins

The inclusive rates for the hadronic penguin diagrams $b \to sg$ (where g denotes a gluon) and $b \to sq\bar{q}$ are estimated to be about 1% from the parton model, but predictions for the hadronization into exclusive final states are uncertain because the simple factorization assumption used for the spectator diagram may not be valid. It is important to systematically measure the exclusive final states where the gluonic penguin contribution is dominant, for example $B \to K_s\phi, K^-\pi^+$ [88]. In future studies at B Factories, some of these modes will be used to search for asymmetries from direct *CP* violation arising from the interference of the penguin and $b \to u$ spectator amplitudes. Although it is not experimentally straightforward, the inclusive $b \to sg$ rate should be also measured and compared to the theoretical expectation. This may be accomplished by searching for a mass peak combining kaon candidates and n pions, where $1 < n < 7$, or by studying inclusive $B \to \phi$ production in the momentum range above the kinematic limit for production from $b \to c$.

5.5 Hadronic Tau Decays

The semi-hadronic decays of the tau can be used to probe the hadronic structure of the electroweak charged current; to measure the parameters of low-mass hadronic resonances with great precision; and to study α_s, QCD sum rules, and spin-sum rules in a new regime [26].

- Hadronic final states are produced by the vector or axialvector component of the W. The conserved vector component of the W can be related, via an isospin rotation, to the electromagnetic current, for which much data exists (from low energy e^+e^- collisions). The vector components of the semi-hadronic decays of the tau (primarily the decays to an even number of pions) can be used as a test of vector current conservation (CVC). There is no comparable body of data in which the partially conserved axial vector hadronic current is cleanly resolvable. Studies of this current may yield new insights into low energy hadronic dynamics. Tau decays into odd numbers of pions provide a unique, clean laboratory to study these hadronic currents.

- Tau decays permit the study of resonances (the ρ, a_1, ρ', etc, and the strange resonances K^*, K_{1A}, K_{1B}, etc) with very clean, high statistics samples. The decays via the strange K_1 resonances allow for interesting studies of the interplay between meson mixing (between the K_{1A} and K_{1B} resonances) and the $SU(3)_f$-violating second-class current (which produces the K_{1B}). The decay to $\pi^-\eta\pi^0\nu_\tau$ proceeds in the Standard Model via the chiral anomaly (the Wess-Zumino coupling), which flips the parity of the three meson system. It is related via CVC and isospin to the cross section for $e^+e^- \to \eta\pi^+\pi^-$. This decay has only been seen by CLEO, with very limited statistics; a larger sample will permit tests of the chiral anomaly and CVC.
- There is a wide range of tests of perturbative QCD and QCD sum rules accessible when studying tau decay spectral functions. The total semi-hadronic decay rate has been used to measure the strong coupling constant at the tau mass scale $\alpha_S(m_\tau)$, and therefore the hadronic scale Λ_{QCD}, with precision comparable to that measured at M_Z. The inclusive semi-hadronic differential decay rate $d, /dq^2$ also provides tests of perturbative QCD, including an independent estimate of the significance of non-perturbative effects. Other QCD predictions can be tested, including the study of polarization in inclusive semi-hadronic tau decays.

6 Facilities

Heavy Flavor Physics is an active part of the program at every existing accelerator laboratory and no doubt will continue to be so no matter what future facilities are supported. This section of our report reviews the programs of existing facilities and approved upgrades, and in addition discusses a number of as-yet-unfunded proposals for extensions, upgrades and new facilities. No attempt has been made to establish priorities for these future efforts. Serious study of the physics reach and costs of each option is needed before that can be attempted, and such a study is beyond the scope of this project.

One area of heavy flavor experiment is not discussed here, and that is possible top-antitop production at hadron colliders or at a future e^+e^- linear collider. See the reports of the Electroweak and Accelerator Working Groups for discussion of these topics.

6.1 K Physics Facilities

6.1.1 Rare K Decay Searches at Brookhaven AGS

The Brookhaven AGS is a 30 GeV proton synchrotron currently producing $> 3 \times 10^{13}$ protons in a 1.3 second spill every 3.8 seconds. Over the past few years the AGS has been undergoing a series of upgrades, which include a new 1.5 GeV Booster, revamped vacuum and RF systems, etc. When these upgrades are completed in FY 1996, the AGS will be able to produce between 6 and 10×10^{13} protons/pulse, making it the most intense source of protons in its energy range. Beam lines will have access to at least five times more protons than available in previous experiments. Rare K decay experiments currently collecting data are designed to reach sensitivities of 10^{-12}/event; these include dedicated searches for the decays $K^+ \to \pi^+\mu^+e^-$, $K_L^0 \to \mu^+e^-$ and $K^+ \to \pi^+\nu\bar{\nu}$. With improvements in beams and detectors, 10^{-13}/event is possible. Such sensitivities are possible at the AGS not only because of the intense fluxes available but because of the powerful particle identification techniques that have been developed to work in the AGS energy range.

The search for $K^+ \to \pi^+\nu\bar{\nu}$ is probably most readily done in stopped K beams. The AGS will soon provide a very pure beam of $> 3 \times 10^6$ stopped K^+/pulse. Experiments involving measurements of muon polarization, such as the currently topical search for T-violation in $K_{\mu3}$ decay also require low energy beams. The important K mode, $K_L^0 \to \pi^0\nu\bar{\nu}$, also needs further study; at low energy determination of the K_L^0 momentum can perhaps augment the otherwise poor signature of this process. Low energy for this experiment also provides a reduction of hyperon backgrounds and the possibility of combining the decay and detection regions for greater acceptance.

With the advent of RHIC, the base costs of maintaining the AGS will be transferred to nuclear physics, making high-energy physics utilization of the machine possibly very economical for the high-energy physics community. However, no decisions have been made.

6.1.2 K Physics at Fermilab

A variety of high precision, high sensitivity Kaon decay experiments can be performed with high energy beams. At high energies, gamma ray energy resolutions become better so that many modes with γ's or π^0's in the final state are well studied. For example, the best sensitivities for the three $K_L^0 \to \pi^0 l\bar{l}$ decays come from Fermilab and these modes are important for the study of *CP* violation. New searches for flavor violation in both K_L^0 and π^0 have been made [89]. A value for the direct *CP*-violation parameter ϵ'/ϵ has been measured as well as the best value of ϕ_{+-}, providing a very sensitive test of *CPT* symmetry.

A new facility to study kaon decay physics is now under construction at the Fermilab Tevatron (KTeV) [90]. The facility should be ready for data taking in late 1995. The center piece of the new detector is a large pure CsI crystal array for electromagnetic calorimetry. A run spanning 1996 and 1997 is planned. Further runs of the facility at even greater intensity are possible at the Tevatron. The facility will eventually be targeted with the even higher intensity but lower energy Main Injector beam as well.

This facility has two thrusts: very high precision studies of two pion decays of both the long and short-lived kaons as a means of determining ϵ'; and studies with high sensitivity for a variety of rare kaon decays.

A measurement of ϵ'/ϵ with a precision near 0.0001 is expected; the Standard Model predicts a signal larger than this value. KTeV, CERN NA48, and DAPHNE are all focusing on this physics and all should have results by 1998.

The rare decay part of KTeV should reach 10^{-11} sensitivity for a variety of multi-body modes. In particular, this allows the continued study of the $\pi^0\mu^+\mu^-$ and $\pi^0e^+e^-$ modes for which predictions indicate that the *CP* violating contributions are roughly at this level. Also, hundreds of events of $K_L^0 \to e^+e^-e^+e^-$ and $K_L^0 \to \pi^+\pi^-e^+e^-$ will be collected. These and other modes give sensitivity, through angular distributions, to non-standard *CP* violating mechanisms.

The Fermilab Main Injector is a rapid cycling 150 GeV accelerator which will replace the existing Main Ring in all its functions. For fixed target experiments, a 120 GeV slow spill capability is included in the design which would allow $3-5\times10^{13}$ protons to be spilled over 1.0 second with a 2.9 seconds cycle time, yielding an average duty factor of 34%. These 120 GeV protons could be used to produce intense neutral or charged kaon beams. The kaon intensities will be such that a statistical sensitivity of 1×10^{-13} can be reached in a one year run [91]. A major focus of Main Injector kaon physics could be the three $K_L^0 \to \pi^0 l\bar{l}$ decay modes. Such measurements would provide a new breadth of information on *CP* violating kaon decay physics. In particular, the parameter η could possibly be measured directly to better than 10%. Such experiments require a highly "hermetic" detector to recognize and veto unwanted decays. Studies indicate that the required levels of sensitivity can probably be achieved, but that this exciting physics is highly challenging.

A further subject of study is whether it is possible that a next generation $K^+ \to \pi^+\nu\bar{\nu}$ experiment can be performed at the Main Injector. Lower-energy experiments with stopping kaons require the $\pi-\mu-e$ decay chain to occur for particle identification. The challenge is to be able to do as well with particle identification at high energy, NOT relying on the $\pi-\mu-e$ decay chain. To make a significant impact, such an experiment should have a sensitivity which reaches the 10^{-12} level.

6.1.3 Kaon Physics at Other Facilities

The detailed discussion of the kaon program of Brookhaven and Fermilab should not be taken to imply that there is no competition from overseas laboratories. KEK, Daphne and CERN all have active programs in this area. For the direct *CP* violation (ϵ'/ϵ) experiments the comparison of CERN and Fermilab results has been important, and both laboratories are now building improved experiments (NA48, KTeV). At CERN the CPLEAR project has been studying a variety of K decays, particularly for tests of *CPT*. At DAPHNE the ϕ Factory under construction may provide a complementary program to the K physics efforts and also offers the possibility of some unique *CPT* tests. At KEK an experiment on $K_L^0 \to \pi^0e^+e^-$ is in progress, and a study of $K_L^0 \to \pi^0\nu\bar{\nu}$ is proposed.

6.2 Tau and Charm Physics Facilities

6.2.1 Tau and Charm Physics at e^+e^- Colliders

Currently, the only e^+e^- facility running in the tau and charm threshold region is the Beijing Electron Positron Collider (BEPC). There is a single detector at this facility, the Beijing Electron Spectrometer (BES), with a design very similar to the earlier Mark III detector at SPEAR. There is a significant U.S. component to the collaboration working with this detector, and continued U.S. involvement in any future upgrade is likely.

The peak luminosity of the BEPC storage ring is $4-5\times10^{30}$ cm^{-2}s^{-1} at an energy of 4 GeV in the center-of-mass. An upgrade to both the accelerator and the detector has been approved, with completion anticipated in the fall of 1995. The luminosity after the upgrade is expected to be 1.5×10^{31} cm^{-2}s^{-1}. Preliminary studies for a possible future "tau-charm factory" are also actively underway in Beijing, with a luminosity goal of order 1×10^{33} cm^{-2}s^{-1}, and 5-10 times higher if a crab crossing beam separation scheme is used.

In addition to threshold region experiments, the e^+e^- colliders discussed below under b-quark physics will also be excellent producers of tau's and particularly of charmed particles, since continuum hadronic events are 40% $c\bar{c}$ and, in addition, B's decay preferentially to charm quarks. CLEO has already produced significant contributions to our knowledge of charmed hyperon, D and τ decays and will continue to do so. Asymmetric

B Factories will produce large D physics samples, and the vertex separation of the B decays plus good particle identification capability will make these excellent laboratories for the systematic study of charmed mesons. Likewise these facilities will produce of order 3×10^7 tau-pairs per year, and thus compete with a tau-charm factory as a place to study the details of tau decays and lifetime. LEP also produces a significant sample of tau events, and has made important contributions to the study of tau decays.

6.2.2 Fixed Target Charm Experiments

Photo- and hadro-production of charm in fixed target experiments with extracted beams at Fermilab and CERN continue to play an important role in the study of charm production and decay. Two experiments are approved for the next fixed target run at Fermilab: E831 (photoproduction) and E781 (hadroproduction). These experiments are expected to provide as many as 10^5 reconstructed events per decay mode. Future experiments with higher interaction rates and using present day technology could reconstruct at least an order of magnitude more decays. This would make possible more sensitive searches for D mixing and rare, effective flavor-changing neutral current decays.

Another unique aspect of fixed target experiments is the ability to study production mechanisms of charm. The recently established leading charm particle production [92] is an example of the type of interesting effects that can be studied. The production of the different charm species may show other differences between fragmentation in hadronic interactions compared to e^+e^- annihilation. The use of different beam types (pions, kaons, protons, photons) to elucidate the production mechanisms has just "scratched the surface" of what would be possible in future experiments which could cover a large kinematic range (in x_F and p_t) with good statistical power. For example the production of leading charmed baryons provides a test of models of diquark production, at present a poorly understood area.

The potential for charm physics in an internal target experiment has not been explored much, but cross sections are high so this may turn out to be interesting, if such facilities are constructed for B physics.

6.2.3 Hadron Collider Charm Experiments

Hadron colliders offer an excellent opportunity to perform high sensitivity charm studies. Most of the charm production occurs at very low transverse momentum. The proper instrument for carrying out these studies is a forward magnetic spectrometer with planar vertex detectors located transverse to the interaction region and within a few millimeters of it. No such experiment has been constructed at the CERN S$p\bar{p}$S or at the Fermilab Tevatron so there are no good measurements of the charm cross section at collider energies. QCD calculations are uncertain because of the low charm quark mass but indicate that 1-3% of the events will have a charm pair at Fermilab or RHIC energies. At a luminosity of 10^{31} cm^{-2} sec^{-1} (already surpassed at FNAL and well within the capabilities of RHIC), more than 10^4 charm events will be produced per second. A partial study of detection efficiencies indicates that between 10^8 and 10^9 fully reconstructed charm decays could be obtained in about 10^7 seconds of running. Triggering, tracking, particle identification, and data acquisition represent significant challenges. However, the high signal to background make this an attractive alternative to experiments at existing fixed target facilities. Such experiments must increase their sensitivity by an order of magnitude to take advantage of the higher luminosity expected to be available at hadron colliders towards the year 2000.

6.3 b Physics Facilities

6.3.1 Symmetric e^+e^- Colliders

Most of what has been learned to date about the b quark has come from symmetric e^+e^- colliders: CESR and DORIS operating at the Υ(4S) resonance, PEP and PETRA operating at center-of-mass energies near 40 GeV, LEP and SLC operating at the Z. For those studies that do not benefit from measuring time development, the Υ(4S) energy is generally preferable. At this energy, CESR is being upgraded to a luminosity of $1 - 3 \times 10^{33}$ cm^{-2}s^{-1}, (comparable to a B Factory) status and the CLEO detector is being modified to take advantage of the luminosity increase. The upgraded facility is well-suited for studying rare B decays, for CKM matrix determination, and for searching for direct CP violation in B decays.

Measurement of B lifetimes requires observing time development, as will measurement of $B_s - \bar{B}_s$ mixing. LEP and SLC are the relevant symmetric facilities here. (For the mixing measurement, the polarization of SLC compensates for its lower luminosity relative to LEP.) Further running at these facilities will improve their B event samples and thus their reach for these measurements.

6.3.2 Asymmetric e^+e^- Colliders

Two asymmetric e^+e^- colliders are under construction, (PEP-II)[93] at SLAC and KEKB[94] at KEK. PEP II reuses the PEP tunnel and much of the PEP ring. This facility will collide 9 GeV electrons with 3.1 GeV positrons, to produce $\Upsilon(4S)$ which decays either to B^+B^- or $B^0\overline{B}^0$. The design luminosity is 3×10^{33} cm^{-2}s^{-1}. Such a facility provides a laboratory well-suited to the study of CP violating asymmetries in the decays of neutral B_d's and searches for such effects in charged B decays. In particular the machine is designed to study the time-dependent asymmetries in the decays of B^0's to *CP* eigenstates such as $J/\psi K_s$, D^+D^-, $\pi^+\pi^-$ and $\rho^0\pi^0$, where the time in question is the time difference between the decay of the two B^0's. These asymmetries then measure two of the three angles of the unitarity triangle, and thus can be directly related to the value of ρ and η in the CKM matrix. While the first of these channels can also be studied at a hadron collider, the remaining channels are very difficult to reconstruct in a hadronic environment because of problems with triggering on such modes and with large backgrounds from other hadrons in the events. Thus there are essential parts of the *CP* puzzle which can probably only be studied at such a facility. The asymmetric B Factory can also achieve a significant program of heavy flavor physics in the b, c and τ sectors [95]. The BABAR detector at PEP-II is presently under construction by an international collaboration including physicists from Canada, China, France, Germany, Great Britain, Italy, Russia, Taiwan and the Ukraine (and possibly other countries) as well as a large US participation.

A similar facility is approved for construction at KEK in Japan. The KEK B Factory is designed to eventually achieve a luminosity of 10^{34} (initially 10^33) cm^{-2}s^{-1}. The circumference of the Tristan tunnel (3018 m), which will be used for this facility is significantly larger than the PEP tunnel (2304 m). The machine is designed with a lower energy asymmetry (8.0 GeV on 3.5 GeV) than PEP-II. A small US contingent is also involved in the KEK B Factory effort.

6.3.3 Future Options at Colliders

The potential of Fermilab collider experiments for b physics could be important for the future U.S. program and needs further study. Existing Fermilab experiments have demonstrated initial capability to detect B events, and are considering upgrades that may give them improved B Physics capability. RHIC has a similar potential if it is used in the *pp* collider mode. The production rate for B mesons is high in such facilities, and in addition they provide baryons containing b quarks. A number of options have been developed by proponents, and are briefly discussed in the following sections.

There are three ways to design a dedicated bottom/charm experiment at a collider: extracted-beam fixed-target, internal fixed-target, or colliding-beam. The comments below summarize some of the ideas that are under consideration, but a serious comparative study is needed to make an adequate judgement of their relative merits.

SSC and LHC design studies suggest that extracted-beam fixed-target b experiments are quite competitive with and in some cases exceed the capability of collider experiments at the same accelerator at high energies. For earlier, lower-energy experiments at Fermilab this has not been born out by experience. However it is expected to be increasingly true at higher energies since the fixed target b cross section rises faster than linearly with the beam energy.

Indeed the HERA-B experiment [96], approved at DESY, aims to discover *CP* violation in B decays. The HERA-B experiment plans to produce B's with a wire target in the 800 GeV beam at the HERA *ep* machine. Interactions rates on the order of 30 MHz must be tolerated to allow this experiment to probe $\sin(2\beta)$ to a precision of 0.1 in $B^0 \rightarrow J/\psi K^0_S$ decays. Internal target experiments at LHC and Fermilab have also been under study.

A dedicated program in B physics at a hadron collider offers complementary opportunities and challenges to those at an e^+e^- B Factory. Whereas measurements at the $\Upsilon(4S)$ will be restricted to the B_u and B_d mesons, measurements with B_s, B_c, and Λ_b, and other species of b hadrons are possible using hadronic collisions. Because of the greater b production cross section in hadronic collisions ($\sigma(b\bar{b}) \simeq 50\mu$b at the Tevatron vs. $\simeq 1$ nb at the $\Upsilon(4S)$), rarer processes can in principle be probed. On the other hand, experiments at an e^+e^- B Factory will operate in a much cleaner environment by virtue of the more favorable ratio of b production cross section to the total cross section (about 1/4 at the $\Upsilon(4S)$ and $\simeq 1/1000$ at the Tevatron) and also due the exclusive $B\bar{B}$ decays of the $\Upsilon(4S)$. The challenge for experiments at hadron machines is in obtaining trigger, tagging, and reconstruction efficiencies sufficiently high to take advantage of the large number of b's produced.

Considerable progress has been made recently in the study of B physics at the Tevatron by CDF. The B_s has been confirmed through the fully reconstructed decay $B_s \rightarrow J\psi/\phi$, and exclusive lifetime measurements have been made for the B^+, B^0 and B_s. These measurements have been made possible by the installation of a silicon vertex detector (SVX) in CDF. The lifetime results are still statistically limited but are competitive with results from LEP. Limits have been set on the rare $B \rightarrow K^{(*)}\mu^+\mu^-$ and $B \rightarrow \mu^+\mu^-$ that are competitive with current results from CLEO. CDF has also measured the polarization correlations in the decay $B^0 \rightarrow J/\psi K^*$ with a precision comparable to that achieved by CLEO, demonstrating the ability to study decay dynamics in the hadron collider environment.

Further progress is expected at the Tevatron as more luminosity is delivered. Upgrades of the tracking systems and trigger and data acquisition electronics for CDF and DØ can increase the capabilities of these detectors for B physics, especially with the luminosities expected ($\sim 10^{32}$ cm^{-2}s^{-1}) when the Main Injector becomes operational.

Initial measurements of $\sin(2\beta)$ from *CP* violation in $B_d \rightarrow J/\psi K_S^0$ decays may be possible at the Tevatron with an integrated luminosity of 1 fb^{-1} [97]. The precision of these measurements will depend strongly on the tagging strategy employed; the possibility of tagging B's with pions from B^{**} or fragmentation processes is being actively pursued. Measurements of *CP* violation in $B_s \rightarrow J/\psi\phi$ and of $B_s - \bar{B}_s$ mixing will also be pursued.

The two existing detectors at the Tevatron Collider, CDF and D0, are primarily designed to explore high p_t physics and are not optimized for B physics investigations even though they have significant capabilities in this area. Efforts continue to design detectors are that are specifically optimized to have the tracking, vertexing, triggering, particle identification, and data acquisition capabilities to study *CP* violation, B_s mixing, and rare B decays at the Tevatron. The goal of these designs is to achieve at least an order of magnitude improvement in sensitivity over an upgraded CDF or D0 detector to a wide variety of *CP* violating and rare B decays.

Additional opportunities can be anticipated eventually at LHC ($\sigma(b\bar{b}) \simeq 700\mu b$, $L = 10^{33}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$) where a program directed at B physics has been endorsed. Another possibility is RHIC. RHIC is scheduled for commissioning in 1999, and will run primarily for nuclear physics (heavy ions), with an anticipated availability of about 20% for high-energy physics, provided HEP funding was available. Calculations show that RHIC, operating in *pp* mode with 250 GeV/c per beam could produce 10^9 B's per month if operated at a luminosity of 4×10^{31} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. RHIC has the attractive features of a short luminous region (11 cm rms), 110 ns between bunch crossings with just over 1 interaction/bunch, 60% of the B's are produced with $\eta < 1.5$. The expected signal-to-background ratio is about a factor of four below that of a Fermilab experiment.

7 Conclusions

The mysteries of mass, flavor, and CP violation, which are likely to have deep connections, compel us to continue pushing an experimental and theoretical program studying the decays of heavy flavor. One goal of this program is to perform sufficient measurements to unambiguously overconstrain the CKM matrix. Another goal is to exploit the sensitivity of searches for rare and forbidden decays to physics beyond the Standard Model governed by mass scales exceeding those that can be directly probed in present or planned accelerators. Because we are unable to predict in which sector (bottom, charm, tau, strange) evidence for physics beyond the Standard Model will appear, our studies need to remain as broad as possible.

Continued progress towards the above goals requires continued experimental and theoretical progress in understanding the interplay of the strong, weak and electromagnetic interactions in decay processes. As examples: the completion of full next-to-leading order QCD corrections to the $b \rightarrow s\gamma$ branching ratio will increase the power of that measurement as a search for beyond-the-Standard-Model physics; accurate lattice-gauge calculations of the B decay constant f_B will relate measurements of $B^0 - \bar{B}^0$ mixing to the CKM matrix element V_{td}.

The present U.S. program in heavy flavor physics is healthy and extensive, and includes CLEO at Cornell (bottom, charm, tau), the collider program at Fermilab (bottom), the fixed target program at Fermilab (charm, strange), and rare kaon studies at Brookhaven. In addition, there is substantial U.S. involvement in the LEP experiments at CERN (bottom, taus), and in BES in Beijing (taus, charm). The approved upgrades to existing facilities (CESR-CLEO, CDF, D0) and the approved SLAC asymmetric B Factory ensure a continued healthy program. A small US group is also participating in the KEK asymmetric B Factory effort.

We recommend a study of the opportunities for dedicated B physics experiments at a collider, or hadronic fixed target experiment, at either Brookhaven or Fermilab. The production rate of b quarks in high-energy hadron-hadron collisions greatly exceeds that in e^+e^- collisions, but triggering, background rejection and resolution all provide challenges. A number of ideas for dedicated B-physics experiments at Brookhaven and at Fermilab have been studied. The desirability of a new facility deserves careful consideration, with comparison of the physics reach it would provide to that given by the e^+e^- B Factories, the Hera-B internal target experiment at DESY, and possible LHC B physics initiatives. If an interaction region currently used for high P_t physics is involved, the loss of that physics should be included in the considerations.

The long-range future of kaon physics needs careful consideration. As Brookhaven's role shifts with the advent of RHIC, the role of kaon experiments at that laboratory will need attention. Similarly at Fermilab the interplay of the kaon program with other initiatives requires on-going attention in resource allocation.

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