SLAC – PUB – 4443
October 1987
T/E

FLAVOR MIXING WITH QUARKS AND LEPTONS*

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ABSTRACT

The last year has brought such a wealth of new information on heavy flavors that meaningful bounds can now be placed on all fermion mass related parameters in the Standard Model. I review the status of the KM matrix with particular emphasis on the theoretical uncertainties. $B^0 - \overline{B}^0$ mixing is reevaluated and CP violation is discussed as it is observed in K_L decays and as it hopefully can be studied in B decays. I conclude with short remarks on neutrino oscillations.

Invited Lecture presented at the

VII-th International Conference on "Physics in Collision"

Tsukuba, Japan, August 25-27, 1987

⋆ Work supported by the Department of Energy, contract DE – AC03 – 76SF00515.
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1. INTRODUCTION

Almost to the day 15 years ago, on September 1, 1972, a truly remarkable paper[1] was received by the journal Prog. Theoret. Phys. In it Kobayashi and Maskawa pointed out that the minimal way to implement CP violation requires three families. With neutrinos being massless one has to deal with nine (non-trivial) masses and four mixing parameters in the quark sector

$$V_{KM} \simeq \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^2(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \end{array} \tag{1}$$

where I have used an approximate expansion in λ suggested by Wolfenstein [2].

We still do not know the precise values of all these parameters; yet this past year has been very exciting in generating strong suggestions that we have now rather non-trivial *upper* and *lower* bounds on all these parameters—as long as we stay within the Standard Model with three families.

In Chapter 2 I will review the phenomenological status of the KM matrix with particular emphasis on $V(cb)$ and $V(ub)$ and their implications for $V(ts)$ and $V(td)$. In Chapter 3 I give a theoretical evaluation of $B^0 - \overline{B}^0$ mixing which yields information on $V(td)$, $V(ts)$ and m_t. In Chapter 4 I employ the observed strength of CP violation in K decays to limit the remaining parameter η and make some predictions of CP asymmetries in B decays. There is one field where I do not see collider physics make any direct contributions—neutrino oscillations; I cannot resist the temptation to discuss it briefly in Chapter 5 before giving my conclusions in Chapter 6.

2. PHENOMENOLOGICAL STATUS OF THE KM MATRIX

Two of the nine matrix elements are very well determined[3]

$$|V(ud)| = 0.974 \pm 0.001 \qquad |V(us)| = 0.220 \pm 0.002 \ . \tag{2}$$

Very similar couplings are—as expected—obtained for the charm couplings[3]

$$|V(cs)| = 0.95 \pm 0.15 \qquad |V(cd)| = 0.207 \pm 0.024 \ . \tag{3}$$

It should be kept in mind that these last two numbers are obtained in a rather indirect fashion; namely, from a study of di-muons in neutrino nucleon scattering where the second muon is attributed to charm production. Thus systematic uncertainties are sizeable and not easily reduced. Detailed studies of D decays have almost reached a competitive level both statistically as well as systematically. We can expect that such studies will yield more precise numbers on $|V(cs)|$, $|V(cd)|$ in the foreseeable future.

$|V(cb)|$ and $|V(ub)|$ control beauty decays, yet it poses quite non-trivial problems to extract numerical values of these parameters from observed B decay rates, for it is the decays of hadrons that can be studied experimentally not that of quarks. Considerable systematic uncertainties are thus introducedright from the start.

For example one can employ the Spectator Ansatz to describe semi-leptonic B decays on the quark level:

$$\Gamma(B \to \ell\nu X) \simeq \Gamma(b \to \ell\nu c) = \frac{G_F^2 m_b^5}{192\pi^3} |V(cb)|^2 K\left(\left(\frac{m_c}{m_b}\right)^2\right) \tag{4a}$$

$$K(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \log x \tag{4b}$$

where we have already anticipated $|V(cb)|^2 \gg |V(ub)|^2$. From the data one then deduces

$$|V(cb)|_{Sp} \simeq 0.045 \pm 0.008 \tag{5}$$

where the uncertainty reflects mainly our uncertainty about the "correct" choice for the quark masses m_b and m_c. We have also assumed implicitly $\tau(B^{\pm}) = \tau(B^0)$—an equality that has been checked experimentally only within a factor of two [4]. There are further uncertainties on how to handle hadronization in these decays. Two quite different model descriptions have been provided by Grinstein, Isgur and Wise (GIW)[5] and by Bauer, Stech and Wirbel (BSW)[6], they yield

$$|V(cb)|_{GIW} \simeq 0.04 \pm 0.01 \tag{6}$$

$$|V(cb)|_{BSW} \simeq 0.053 \pm 0.01 \ . \tag{7}$$

Therefore

$$|V(cb)| \sim 0.033 - 0.066 \tag{8}$$

where the systematic uncertainties clearly dominate.

It was already stated that $|V(ub)|$ has to be different from zero—otherwise CP violation cannot be implemented in the Standard Model (with three families). Yet one clearly wants to obtain more direct experimental information on it. Searches have been performed in semi-leptonic as well as non-leptonic B decays.

No clear signal has been found in various analyses of semi-leptonic B decays. The supper bound on $|V(ub)|$ derived from that depends on the hadronization scheme adopted:

$$\left|\frac{V(ub)}{V(cb)}\right|_{GIW} \lesssim 0.19 \tag{9}$$

$$\left|\frac{V(ub)}{V(cb)}\right|_{BSW} \lesssim 0.11 \tag{10}$$

and considerably smaller bounds are obtained when free quark decay models are used[4].

Again it has to be stressed that at our present understanding (or lack thereof) of the hadronization process in semi-leptonic decays one cannot just quote numbers on $|V(ub)|$, $|V(cb)|$, but *has to state at the same time which hadronization scheme was used in the analysis.*

The ARGUS collaboration has presented highly intriguing evidence for $b \to u$ mediated transitions in B decays:

$$BR(B^+ \to p\bar{p}\pi^+) = (3.7 \pm 1.3 \pm 1.4) \times 10^{-4} \tag{11}$$

$$BR(B^0 \to p\bar{p}\pi^+\pi^-) = (6.0 \pm 2.0 \pm 2.2) \times 10^{-4}\ . \tag{12}$$

These numbers, if confirmed, establish directly that $|V(ub)| \neq 0$. However at the moment one cannot extract very precise values for it; typical guesstimates are[7]

$$0.1 \lesssim \left|\frac{V(ub)}{V(cb)}\right| \lesssim 0.4\ .$$

Accepting the bounds from semi-leptonic decays (9), (10) at more or less face value one arrives at

$$0.1 \lesssim \left|\frac{V(ub)}{V(cb)}\right| \lesssim 0.25\ . \tag{14}$$

Employing the unitarity of the 3×3 matrix, see Eq. (1), one concludes

$$|V(ts)| \simeq |V(cb)|\ . \tag{15}$$

Unfortunately no such clear-cut relation exists between $|V(td)|$ and $|V(ub)|$. From

(14) one derives

$$0.4 \lesssim \rho^2 + \eta^2 \lesssim 1.3 \tag{16}$$

and thus

$$|V(td)| \lesssim 0.021\ . \tag{17}$$

It should be noted that the *sign* of ρ is crucial for $|V(td)|$! One needs

$$\rho < 0 \tag{18}$$

to get even close to the bound (17).

3. $B^0 - \overline{B}^0$ MIXING: A THEORETICAL REEVALUATION

(1) Experimental Evidence

In its study of B decays on the $\Upsilon(4s)$ ARGUS has reported [8] finding events that within the Standard Model require the presence of $B^0 - \overline{B}^0$ mixing. More specifically they deduced from their signal

$$\chi(B_d) \equiv \frac{\Gamma(B_d \to \overline{B}_d \to \overline{X})}{\Gamma(B_d \to X)} = 0.17 \pm 0.05 \tag{19}$$

where I have used the notation $B_q = (\bar{b}q)$. (Some so far untested assumptions—like $b_{SL}(B^{\pm}) = b_{SL}(B_d)$, $N(B_d\overline{B}_d)\ :\ N(B^+B^-) = 45 : 55$—went into extracting these numbers; they should therefore be taken with a grain of salt.) Since[9]

$$\chi = \frac{x^2}{2(1+x^2)}\ , \quad x = \frac{\Delta m}{\Gamma} \tag{20}$$

one concludes

$$x(B_d) \simeq 0.73 \pm 0.17 \tag{21}$$

reflecting a truly tiny mass difference

$$\left.\frac{\Delta m}{m}\right|_{B_d} \sim 10^{-13} \ .$$

Yet the more significant observation derived from (20), (21) is

$$\Delta m_B = \mathcal{O}(G_F^2) \tag{22}$$

i.e., Δm_B is equivalent to a higher order electroweak process! In the Standard Model it is given by a loop diagram, i.e. represents a quantum correction. For the same reason it possesses a high sensitivity to the presence of New Physics.

Nature was kind(?) enough to provide us with a second neutral B meson that can exhibit mixing, the B_s. Above the $\Upsilon(4s)$ one always has to deal with a cocktail of various beauty hadrons—$B^{\pm}, B_d, B_s, \Lambda_b$, etc. Thus at present one can only measure a mixing strength which represents a weighted average over B_d and B_s mixing. K. Eggert has presented the UA1 analysis on like-sign dimuons at this conference [10]. Subtracting the Drell-Yan contribution they obtain

$$\langle\chi\rangle_{UA1} = 0.158 \pm 0.059 \tag{23}$$

which is not in clear conflict with the upper bound reported by MARK II[11]

$$\langle\chi\rangle_{MKII} \leq 0.12 \qquad (90\% \ CL) \tag{24}$$

in particular when one includes the MAC findings[12]

$$\langle\chi\rangle_{MAC} = 0.21 \begin{array}{l} +0.29 \\ -0.15 \end{array} . \tag{25}$$

Using $\chi(B_d)$ as reported by ARGUS one could extract $\chi(B_s)$ from $\langle\chi\rangle$—if one only knew the relative production probabilities of B_d and B_s mesons. Those are unknown at present and we can rely only on more or less reasonable guesses:

(*i*) if $N(B_u)$: $N(B_d)$: $N(B_s)$: $N(\Lambda_B) \sim 0.4 : 0.4 : 0.2 :\sim 0$ one concludes

$$\chi(B_s) \lesssim 0.38 \ . \tag{26}$$

(*ii*) if instead the ratios 0.375 : 0.375 : 0.15 : 0.1 were to hold even the maximally possible value for $\chi(B_s)$ is allowed

$$\chi(B_s) \leq 0.5 \ . \tag{27}$$

(2) Theoretical Estimates

There are various rather general arguments—sufficiently convincing to me—that the quark box contribution offers an excellent approximation to Δm_B [9]:

$$\Delta m_B|_{theoret.} \simeq \Delta m_B|_{box} \ . \tag{28}$$

This is in marked contrast to Δm_K! One then finds

$$\Delta m_B \simeq \eta_{QCD} \frac{G_F^2}{6\pi^2} B_B f_B^2 \xi_t^2 m_B E(m_t^2/M_W^2) \tag{29}$$

where $\xi_t = V(tb)V^*(tq)$; η_{QCD} represents the radiative QCD corrections ($\eta_{QCD} \lesssim 1$) and $E(m_t^2/M_W^2)$ describes the dependence on the mass of the internal quarks as first calculated in full generality by Inami and Lim [13]; $B_B f_B^2$ finally calibrates the size of the relevant matrix element

$$\left\langle \overline{B}^0 \middle| (b\overline{q})_{V-A}(b\overline{q})_{V-A} \middle| B^0 \right\rangle \equiv \frac{4}{3} B_B f_B^2 m_B^2 \ . \tag{30}$$

Based on rather general arguments, we have a fairly clear idea on the size of these quantities:

$$B_B \sim O(1) \qquad f_B \sim O(f_\pi, f_K) \ .$$

Unfortunately this information is not good enough; for

$$f_B \to 2 f_B$$

leads to

$$\Delta m_B \to 4 \Delta m_b \qquad x^2 \to 16 x^2$$

changing χ, see Eq. (20), roughly by an order of magnitude; to obtain more explicit numbers on B_B and f_B one has to employ some models for the B meson wave function; this certainly dilutes the mathematical rigor of our predictions since one is dealing with long distance dynamics. Lattice calculation will hopefully settle these issues in the foreseeable future—but not yet.

Scanning models one finds[9]

$$Bf^2|_{B_d} \sim (60 - 220\, MeV)^2 \simeq (4 \times 10^{-3} - 0.05)(GeV)^2 \tag{31}$$

$$Bf^2|_{B_s} \gtrsim Bf^2|_{B_d} \ . \tag{32}$$

Using the available information on $V(cb)$, $V(ub)$ one obtains [14]

$$|V(td)| \leq 0.021 \tag{33}$$

$$\frac{|V(ts)|^2}{|V(td)|^2} \simeq \frac{20}{((1-\rho)^2 + \eta^2)} \gtrsim 5 \ . \tag{34}$$

Equation (34) coupled with (32) and (21) leads to

$$x(B_s) \gtrsim 5x(B_d) \gtrsim 2.8 \tag{35}$$

and

$$\chi(B_s) \gtrsim 0.44 \tag{36}$$

i.e. $B_s - \overline{B}_s$ mixing has to be nearly maximal if indeed $\chi(B_d) \geq 0.12$. The data on $\langle\chi\rangle$ do not contradict Eq. (36)—unless B_s production is only moderately suppressed relative to B_d production, see Eq. (26). However it is quite conceivable that future data will rule out near maximal $B_s - \overline{B}_s$ mixing while confirming sizeable $B_d - \overline{B}_d$ mixing. In that case one would have to invoke the presence of New Physics contributing destructively to $\Delta m(B_s)$! The mildest extension of the Standard Model would be to postulate the existence of a fourth family: such a scenario[15] could well accommodate $\chi(B_d) \sim 0.15$ and $\chi(B_s) \lesssim 0.4$ (while of course not predicting it).

The answer to the question: "To which degree can one accommodate sizeable $B_d - \overline{B}_d$ mixing?" is more ambiguous. The uncertainties on the KM parameters and hadronic wavefunctions can be expressed in units of a calibration factor F

$$F = \frac{|V(td)|^2}{(0.01)^2}\,\frac{Bf_B^2}{(150\,MeV)^2}\;. \tag{37}$$

The discussion given above leads to the range

$$F \sim 0.5 - 7\;. \tag{38}$$

If indeed

$$\chi(B_d) > 0.09 \tag{39}$$

one then concludes[14]

$$m_t \gtrsim 50\;GeV \tag{40}$$

with $m_t \sim 70 - 100\;GeV$ more likely values. A violation of the bound (40)—or its future refinements—would again indicate the presence of New Physics. A note of caution is however appropriate: while (38) represents in my judgment a fairly conservative estimate of the uncertainties—a belief shared by most authors [16] — it is not a prime example of mathematical rigor; secondly, considering the present statistical level of the ARGUS data, one cannot rule out substantial violations of the lower bound (39).

A comprehensive analysis of electroweak phenomena has produced an upper limit on the top mass[3]

$$m_t \lesssim 180 \ GeV \ . \tag{41}$$

Otherwise radiative corrections involving t and b quarks introduce an unacceptably large SU(2) breaking.

4. CP VIOLATION

Everybody seems to agree to the following three statements:

- CP violation has been observed in K_L decays;
- CP violation has not been fully understood yet;
- despite its shy appearance in K_L decays, it represents a very fundamental problem.

Concerning the second statement it should be added that due to the paper by Kobayashi and Maskawa we have acquired a better understanding on the different ways to introduce CP violation into a theory. The three generic ways which were already included in the KM paper are:

(i) Non-trivial mixing among at least three quark families;

(ii) mixing between three (or more) Higgs doublets;

(iii) the existence of right-handed currents.

(1) K_L Decays

One usually adopts the strategy to use the experimental value for ϵ_K as input, extract from it the size of the basic parameter describing CP violation and then make predictions for ϵ' (and d_N, the neutron electric dipole moment).

(a) The Standard KM Ansatz: Using the Wolfenstein representation, Eq. (1), one finds for $30\ GeV \leq m_t \leq 180\ GeV$"

$$B_K \eta \simeq \frac{0.53}{A^2} \left\{0.94\, x_t^{0.1105} - 0.3 + A^2(1-\rho)x_t^{0.8363}\right\}^{-1}$$

$$x_t = \frac{m_t^2}{M_W^2} \tag{42}$$

where B_K is defined in analogy to B_B, Eq. (30). If for example $B_K = 2/3$—a perfectly reasonable value from our present understanding—one infers for $m_t = 60\,[130]\ GeV$, $\rho < 0$

$$\eta \sim 0.5\ [0.2] \tag{43}$$

If however $B_K \simeq 1/3$ and $m_t < 60\ GeV$ were to hold one could not accommodate the observed size of ϵ_k without violating the bounds on $|V(ub)|$.

Employing Penguin operators one finds for $\eta \sim 0.5\,[0.2]$ [17]

$$\frac{\epsilon'}{\epsilon} \sim 7\,[3] \times 10^{-3} \left(\frac{\mathrm{Im}\,\tilde{c}_6}{-0.1}\right) \left(\frac{\langle \pi\pi|Q_6|K^0\rangle}{1.0(GeV)^3}\right) . \tag{44}$$

Q_6 denotes the Penguin operator and $\tilde{c}_6$ its coefficient in the Wilson expansion of $\mathcal{L}_{\rm eff}(\Delta S = 1)$. The perturbative computation of $\mathrm{Im}\,\tilde{c}_6$ which yields -0.1 should be fairly reliable since only momenta between $\sim m_c$ and $\sim m_t$ contribute when CP violation is concerned. The value of the matrix element of Q_6 is much more uncertain: different models yield values between 0.3 and 1 $(GeV)^2$. Thus

$$\frac{\epsilon'}{\epsilon} \sim O(few \cdot 10^{-3}) . \tag{45}$$

This would be quite consistent with the beautiful most recent measurements[18]

$$\frac{\epsilon'}{\epsilon} = (3.5 \pm 0.6 \pm 0.4 \pm 1.2) \times 10^{-3} \ . \tag{46}$$

It is not completely academic to add a further note of caution: a very large m_t implies a rather small η since ϵ_K is fixed; in that case one might expect $\epsilon'/\epsilon \lesssim 10^{-3}$ to hold in the Standard Model with three families only.

Unobservably small values are predicted for d_N, the neutron electric dipole moment:

$$d_N \lesssim 10^{-30} ecm \ . \tag{47}$$

(b) Beyond the Standard KM Ansatz: KM 'B" or the Weinberg Ansatz

CP violation is here attributed to non-trivial mixing between three different Higgs field doublets. It has been pointed out some time ago by Sanda and by Deshpande [19] that one typically finds

$$\frac{\epsilon'}{\epsilon} \sim \mathcal{O}(-0.05) \tag{48}$$

which is clearly inconsistent with the experimental findings—unless chiral symmetry introduces a sufficiently strong suppression. This might just conceivably happen though it is hard to see how $\epsilon'/\epsilon \sim \mathcal{O}(10^{-3})$ could be accommodated that way; ϵ_K is then generated mainly due to $K^0 \to \eta, \eta' \to \overline{K}^0$ with a hefty dependence on long distance dynamics and their uncertainties. Even so one can obtain a fairly conservative *lower* bound on d_N[20]

$$d_N \gtrsim 10^{-24} ecm \tag{49}$$

which is very close to being in conflict with the data

$$d_N\big|_{exp} \lesssim \mathcal{O}(few \cdot 10^{-25}\ ecm) \ . \tag{50}$$

This model is thus seriously wounded and soon might be ruled out as a significant contributor to CP violation at low energies.

(2) B Decays

When adopting the Standard KM prescription one is lead by quite general arguments to expect very sizeable CP asymmetries to emerge somewhere in beauty decays. Since at present it is premature to quote precise numerical predictions on the size of the asymmetry and the corresponding decay mode, I will concentrate instead on a classification with generic examples.

CP violation is established most directly by observing a difference between CP conjugate decay rates. When comparing $\Gamma(B(t) \to f) = e^{-\Gamma t} G$ with $\Gamma(\overline{B}(t) \to \overline{f}) = e^{-\Gamma t} \overline{G}$ one can encounter two basic types of differences

$$G/\overline{G} \not\equiv 1 \, , \quad \frac{d}{dt}(G/\overline{G}) = 0 \tag{51}$$

$$G/\overline{G} \not\equiv 1 \, , \quad \frac{d}{dt}(G/\overline{G}) \neq 0 \, . \tag{52}$$

Scenario (51) holds when a CP asymmetry requires the presence of final state interactions; scenario (52) when $B^0 - \overline{B}^0$ mixing is involved.

(a) CP asymmetries and final state interactions (FSI) The most interesting realization—in my judgment—is provided by invoking Penguin contributions, as first suggested by Bander, Silverman and Soni [21]. Doing detailed calculations one finds typically

$$\begin{gathered} BR(B \to K^\pm \pi^\mp) \sim \mathcal{O}(10^{-5}) \\ \left| \frac{\Gamma(B^0 \to K^+\pi^-) - \Gamma(\overline{B}^0 \to K^-\pi^+)}{\Gamma(B^0 \to K^+\pi^-) + \Gamma(\overline{B}^0 \to K^-\pi^+)} \right| \sim 1 - 10\% \end{gathered} \tag{53}$$

independent of decay time since the time distribution of $B \to K^\pm \pi^\mp$ is given by a single exponential.

(b) CP asymmetries and $B^0 - \overline{B}^0$ mixing: $B^0 - \overline{B}^0$ mixing is a coherent process— therefore it has the potential to expose the complex phase of physical coupling constants. Since mixing is typically studied by analyzing like-sign dileptons in $B\overline{B}$ events, it is quite natural to search for a CP asymmetry there as well

$$a_{SL} = \frac{\sigma(B^0\overline{B}^0 \to \ell^+\ell^+X^{--}) - \sigma(B^0\overline{B}^0 \to \ell^-\ell^-X^{++})}{\sigma(B^0\overline{B}^0 \to \ell^+\ell^+X^{--}) + \sigma(B^0\overline{B}^0 \to \ell^-\ell^-X^{++})} \, .$$

Detailed calculations yield however extremely gloomy results

$$a_{SL} = \begin{cases} \lesssim 10^{-3} & \text{for} \quad B_d \quad \text{mesons} \\ \lesssim 10^{-4} & \qquad\;\; B_s \end{cases} \tag{54}$$

Yet this is not the end of the story; it only means that

$$\mathrm{Re}\,\overline{\epsilon}_B \ll 1 \tag{55}$$

and does not exhaust all aspects of CP violation as discussed by Sanda and coworkers [22]. For when there is a final state f *common* to both B^0 and $\overline{B}^0$ decays—in the Standard Model, this is necessarily a non-leptonic mode—then one finds

$$\text{rate}\,(B^0(t) \to f) \propto e^{-\Gamma t}\left(1 + \sin\Delta mt\,\mathrm{Im}\,\frac{q}{p}\,\rho_f\right) \tag{56}$$

$$\text{rate}\,(\overline{B}^0(t) \to f) \propto e^{-\Gamma t}\left(1 + \sin\Delta mt\,\mathrm{Im}\,\frac{p}{q}\,\frac{1}{\rho_f}\right) \tag{57}$$

where

$$\frac{q}{p} = \frac{1-\epsilon_B}{1+\epsilon_B} \, , \quad \rho_f = \frac{Ampl(\overline{B}^0 \to f)}{Ampl(B^0 \to f)} \, .$$

–I have assumed $\left|\frac{p}{q}\right|^2 \simeq 1$, $\Delta\Gamma_B = 0$ as expected in the Standard Model.

Such asymmetries evidently require the presence of mixing to become observable since $(\sin\Delta mt) \to 0$ as $\Delta m \to 0$. Im $\frac{q}{p}\,\rho_f$ is intrinsically connected with CP violation. The final state f can be a CP eigenstate like $B_d, \overline{B}_d \to \psi K_s, D\overline{D}$, but does not have to be, e.g. $B_d, \overline{B}_d \to D^{\pm}\pi^{\mp}$. The underlying principle is the same in both cases, there are only calculational differences. For simplicity I will focus on CP eigenstates; one typically finds

$$\mathrm{Im}\,\frac{q}{p}\,\rho_f(B_d \to \psi K_s, D\overline{D}) \simeq \frac{2\eta(1-\rho)}{(1-\rho)^2+\eta^2} \sim 0.5\,[0.2] \tag{58}$$

if $m_t \simeq 60\,[130]\;GeV$, i.e. very large numbers leading to the expectation of big asymmetries.

For $B_s \to \psi\phi, F\overline{F}$ one finds relatively small asymmetries on the order of a few percent at most. However if there is a fourth family or if one studies rare modes like $B_s \to D^0\phi$ [23] one typically finds numbers on the same level as those in (58).

In conclusion: adopting the KM prescription one predicts large CP asymmetries in B decays. Asymmetries around 10% are quite realistic; predictions of 50% effects are optimistic, yet not ridiculous.

5. NEUTRINO OSCILLATIONS

As long as neutrinos are massless, as in the Standard Model, mass eigenstates of leptons are necessarily flavor eigenstates and there is no analogue of Cabibbo-Kobayashi-Maskawamixing of quark flavors. Yet there is no good structural reason for neutrinos being massless; on the contrary a nice mechanism —the "see-saw mechanism"— has been suggested [24] which will give a small, yet finite mass to neutrinos:

$$m_\nu \sim \frac{m_D^2}{M} \tag{59}$$

where M denotes a unification scale, say $M \sim 10^{11}\,GeV$, and m_D a "typical" Dirac mass, say 10 GeV. Then $m_\nu \sim 1\,eV$.

When there are neutrino masses, the mass eigenstates will in general not be lepton flavor eigenstates anymore—hence neutrino oscillations. Ignoring neutrino decays one finds for the probability of a neutrino born as an "a"-type neutrino to turn into a "b"-type neutrino after traveling a distance R:

$$\text{Prob}\ (\nu_a(0) \to \nu_b(R)) = (KM_{ij})^2 \sin^2\left(\frac{\Delta m^2_{ij} R}{4E_\nu}\right) . \tag{60}$$

The experimental parameters are the distance R and the beam energy E_ν. What one aims at measuring are the mass differences between the mass eigenstates $\nu_{i,j}$—Δm^2_{ij}—and their mixing angles—KM_{ij}.

Searches for neutrino oscillations have been performed for quite some time now—with no established positive signal so far. Tantalizing hints have appeared periodically in the past—as it has happened again in the past year or so at two BNL experiments [25]. We can only hope that perseverance will be rewarded with luck.

6. SUMMARY

(1) For the first time we can claim that all fermion mass related parameters of the Standard Model with three families are constrained in a meaningful fashion

$|V(ud)| = 0.974 \pm 0.001$

$|V(us)| = 0.220 \pm 0.002$

$$\left.\begin{array}{r} |V(cs)| = 0.95 \pm 0.15 \\ |V(cd)| = 0.107 \pm 0.024 \end{array}\right\} \text{ significant theoretical uncertainties}$$

$|V(cb)| = 0.033 - 0.066 \simeq |V(ts)|$ considerable theoretical uncertainties

$$\left.\begin{array}{r} 0.1 \lesssim \left|\frac{V(ub)}{V(cb)}\right| \lesssim 0.25 \\ 45GeV \lesssim m_t \lesssim 180\ GeV \end{array}\right\} \text{ large uncertainties of any kind}$$

Even so, the level of what is meant by state of the art precision has clearly risen.

(2) There is good evidence that sizeable $B_d - \overline{B}_d$ and possibly large $B_s - \overline{B}_s$ mixing has been observed. These are very important phenomena since they are given by quantum corrections in the Standard Model and provide sensitive probes of New Physics. Confirmation of these effects is clearly desirable, in particular in reactions like $e^+e^- \to B_s + X$. Such searches are not easy; the recent work of Seiji Ono, Sanda and Tornquist is quite relevant in this context.

(3) (a) For the first time we can say that a signal for direct CP violation is emerging in K_L decays: $\epsilon'/\epsilon \neq 0$. (b) Needless to say a search for CP violation in B decays represents an awesome challenge. Yet this task promises not only a glittering prize—an understanding on the origins of CP violation; even better, it does not appear completely hopeless, since CP asymmetries of order 10 to 50% are anticipated. Discussions of this program have now moved from the County Fair to the laboratory.

(4) Searches for neutrino oscillations are as tantalizing (or agonizing?) as ever. I hope vigorous research will continue. Some stroke of luck is clearly needed—but is that not true for all fields of science?

Acknowledgements

It was a pleasure to participate in a meeting that was so smoothly organized by Professor K. Takahashi and his coworkers. I greatly benefitted from numerous discussions with colleagues, in particular Seiji Ono, A. Sanda and W. Marciano.

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