SUMMARY
OF
WEAK DECAYS, CKM AND CP VIOLATION SESSION
PENGUINS

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In our subgroup, we focused on penguin physics from various different angles. Our discussions included: (1) A method to extract one of the angles of the unitarity triangle $\phi_2$; (2) Methods to extract $\phi_3$ from $B \to K\pi$ decays; (3) Effects of non-minimal SUSY on B and K decays; (4) Understanding large branching ratios for $B \to \eta' + K(K^*)$ decays; (5) New calculation for hadronic matrix elements which are needed to compute $\epsilon'$.  

1 Introduction

Our session was given a rather general title: "Weak Decays, CKM and CP Violation". It is a big field and we can not do justice to any of these subjects if we try to cover everything. For this reason, we decided to concentrate our discussion on penguin physics.

Year 1998 was a very good year for penguin physics - year 1999 promises to be even better for flavor physics in general.

1. We are supplied with branching ratios on hadronic two body decays from CLEO:\[\text{(1)}\]

$$\begin{align*}
\text{Br}(B^\pm \to K^\pm \pi^0) &= (1.5 \pm 0.4 \pm 0.3) \times 10^{-5}, \\
\text{Br}(B^\pm \to K\pi^\pm) &= (1.4 \pm 0.5 \pm 0.2) \times 10^{-5}, \\
\text{Br}(B \to K^\mp \pi^\pm) &= (1.4 \pm 0.3 \pm 0.1) \times 10^{-5}, \\
\text{Br}(B \to \pi^\mp \pi^\pm) &= \left(0.37^{+0.20}_{-0.17}\right) \times 10^{-5}, \\
\text{Br}(B \to \pi^\mp \pi^0) &= \left(0.59^{+0.32}_{-0.27}\right) \times 10^{-5}.
\end{align*}$$

1
2. New results on $\epsilon'$ was promised, and in fact, just after the meeting the result from E832 was announced. The result is considerably larger than that of previous Fermilab result:

$$\text{Re} \frac{\epsilon'}{\epsilon} = \begin{cases} 
(23 \pm 6.5) \times 10^{-4} & \text{NA31} \\
(28.0 \pm 0.30_{\text{stat.}} \pm 0.26_{\text{syst.}} \pm 0.10_{\text{MC-stat.}}) \times 10^{-4} & \text{E832}
\end{cases}$$

This result is now in agreement with that from CERN and establishes non-vanishing direct CP violation.

3. Belle and Babar collaborations should start taking data on much anticipated large CP violation in B decays. Along the way, there will get lots of data on B decays.

4. A new K meson factory at DaΦne should start taking data this year.

Who knows, by year 2001, we may have a positive signal for New Physics. Much of above experimental development demands better theoretical understanding of penguins.

2 How big are penguins?

Let us illustrate the importance of penguins by giving a hand-waving argument based on the experimental result Eq. (1). Less hand-waving argument is presented in Gronau’s contribution.

The amplitudes for tree and penguin contributions for $K\pi$ decay mode are:

$$T(K\pi) = \frac{G_F}{\sqrt{2}} V_{ub} V_{us} [C_1(\mu)Q_{s1}^u(K\pi) + C_2(\mu)Q_{s2}^u(K\pi)]$$

$$P(K\pi)_c = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs} [C_1(\mu)Q_{s1}^c(K\pi) + C_2(\mu)Q_{s2}^c(K\pi)]$$

$$P(K\pi)_t = \frac{G_F}{\sqrt{2}} (-V_{tb}^* V_{ts}) \sum_{i=3}^{10} C_i(\mu)Q_{s1}(K\pi).$$

(2)

To simplify our notation, set:

$$T(K\pi) = V_{ub}^* V_{us} T; \ P(K\pi)_c = V_{cb}^* V_{cs} P^c; \ P(K\pi)_t = -V_{tb}^* V_{ts} P^t.$$  

(3)

If penguin diagram gave negligible contribution, the entire two body decays occur through Fig. 1(a). Then $B \to \pi\pi$ decay goes through a diagram in which the $s$ quark in Fig. 1(a) is replaced by a $d$ quark. For a rough argument, we
ignore SU(3) breaking in the hadronic matrix elements. Then, \( B \to \pi \pi \) is given by \( T(\pi \pi) \sim \lambda^3 T \). Since \( T(K\pi)/T(\pi \pi) \sim \lambda \), we would expect:

\[
\text{Br}(B \to K\pi)/\text{Br}(B \to \pi \pi) \sim O(\lambda^2). \tag{4}
\]

Experimentally this is not so. This indicates that the \( P(K\pi) \) amplitude is at least as large as the \( T(\pi \pi) \).

For \( B \to K\pi \), \( P(K\pi) \) is \( O(\lambda^2) \) and \( T(K\pi) \) is \( O(\lambda^4) \). So, \( P(K\pi) \) must be a major contributor to the decay amplitude. If \( P(K\pi) \simeq T(\pi \pi) \), then

\[
\frac{P^c + P^t}{T} = O(\lambda), \tag{5}
\]

the penguin contribution is considerably larger than what a naive estimate of the loop graph would suggest:

\[
\frac{P^c + P^t}{T^u} \sim \frac{\alpha_S}{12\pi^3} \log \frac{m_t}{m_c} \sim O(0.01). \tag{6}
\]
Gronau went through less hand-waving analysis and obtained
\[ \frac{P^c + P^t}{T_u} = 0.3 \pm 0.1. \] (7)

Large penguin contribution is not always welcome. For example, they play a role in so called "penguin pollution" which causes hadronic uncertainty in determining \( \phi_2 \) and \( \phi_3 \). For notations see Fig. 2. Problem penguins cause, however, does not compare with richness they bring to flavor physics. Unlike in K decays where effects of tree graphs dominate, in B physics, quantum loop effects via penguins is often a leading contribution. This gives us a window of opportunity to look for effects beyond the standard model - as they are likely to contribute through loop effects. Anticipating this possibility, we had the following discussions:

1. Reviews of penguins in B decays by M. Gronau.
2. New remarks on the determination of \( \phi_1 \) and \( \phi_2 \) by L. Oliver.
3. A critical look at \( \phi_3 \) from \( B \to K \pi \) by R. Fleischer.
4. Model independent analysis of \( B \to K \pi \) decays and bounds on the weak phase \( \phi_3 \) by M. Neubert.
5. Analysis of \( B \to \eta K(K^*) \) and \( B \to \eta' K(K^*) \) by D-D. Du.
6. Effects of SUSY particles in B and K decays by A. Masiero.
7. Chiral methods and predictions for \( K \to \pi \pi \) by E. Paschos.

\footnote{Here we use the notation which was introduced when the unitarity triangle was first discussed in the context we use today.}
3 Taming the penguins

How to get around the penguin pollution and extract the value of $\phi_2$ has been reviewed by Gronau. Oliver has presented an alternative approach which may be useful. In his approach, $\phi_2$ is expressed as a function of experimentally measurable quantities in $B \to \pi\pi$ decay, plus one other parameter. It can be, for example, $\frac{q}{p}$, obtained from $B \to K\pi$, mentioned above.

The time dependent $B(B) \to \pi^+\pi^-$ decay rates are given by:

$$\Gamma \left( B \to \pi^+\pi^- \right) (t) \sim \left[ |A|^2 + |A'|^2 \pm (|A|^2 - |A'|^2) \cos(\Delta M_B t) \right]$$

$$\pm 2 \text{Im} \left( \frac{q}{p} A^* \right) \sin(\Delta M_B t) \right]. \quad (8)$$

There are three experimental observables:

$|A|$, $|A'|$, and $\text{Im} \left( \frac{q}{p} A^* \right)$.

Theoretically, we can write

$$A = V_{ud} V_{ub}^{*} M^u + V_{td} V_{tb}^{*} M^t$$

$$= V_{ud} V_{ub}^{*} M^u \left[ 1 - \left| \frac{V_{td} V_{tb}^{*}}{V_{ud} V_{ub}^{*}} \right| e^{i\phi_2} M^t \frac{M^u}{M^u} \right]. \quad (9)$$

Here $M^u = T^u - \mathcal{P}^c$, and $M^t = \mathcal{P}^t - \mathcal{P}^c$. These are related to previously introduced matrix elements except for the SU(3) breaking corrections.

Theoretical unknowns are

$|M^u|$, $\left| \frac{M^t}{M^u} \right|$, $\arg \left( \frac{M^t}{M^u} \right)$, $\phi_2$.

Since there are 4 theoretical parameters and only 3 experimental observables, we cannot solve for $\phi_2$. We can, however, solve for $\phi_2$ as a function of, e.g. $\left| \frac{M^t}{M^u} \right|$. We can, most likely obtain this parameter from Eq. (16) looking at $B \to K\pi$ decays. Further study is necessary to see how the error from SU(3) symmetry breaking will affect the determination of $\phi_2$. Also, there are some ambiguities coming from the sign of a square root as well as that coming from $\phi_2 \pm \pi$. For details see Oliver’s talk.\[\]
4 Getting maximum out of $B \to K\pi$, $\pi\pi$ decays

The CLEO collaboration has recently reported the observation of $B \to K\pi$ decays given in Eq. (1). It is clearly important to understand what we can learn from these results. Contributions from Fleischer, Gronau, and Neubert on this subject are rather technical. Nevertheless, it is an important technicality, as it must be understood when information is extracted from data. So, rather than summarizing what they have presented, I have presented necessary formalism which I hope is useful in following their work.

Feynman graphs shown in Fig. 1 illustrates the class of operators which are generated by QCD and electroweak radiative corrections. The weak Hamiltonian which causes these decays can be written as

$$\mathcal{H} = \frac{G_F}{\sqrt{2}} \left\{ \xi_u [C_1(\mu)O^u_1 + C_2(\mu)O^u_2] + \xi_c [C_1(\mu)O^c_1 + C_2(\mu)O^c_2] \right\} + \text{h.c.},$$

(10)

where $\xi_q = V^*_{qb}V_{qs}$, $O^u_1 = (\bar{b}s)_{V-A}(\bar{q}q)_{V-A}$ and $O^u_2 = (\bar{b}q)_{V-A}(\bar{q}s)_{V-A}$, $O_9 = \frac{3}{2}(\bar{b}s)_{V-A} \sum_q e_q(\bar{q}q)_{V-A}$, $O_{10} = \frac{3}{2}(\bar{b}q)_{V-A} \sum_q e_q(\bar{q}s)_{V-A}$. Let us try to understand the isospin structure of these operators. The up tree graph Fig. 1(a) contains $u$ and $\bar{u}$ quarks and they generate both $\Delta I = 0$, and $\Delta I = 1$ terms in the effective Hamiltonian. Fig. 1(b), the charm tree graph, contains all isosinglet quarks and thus they generate $\Delta I = 0$ operator. Fig. 1(c), the penguin, gives contribution which is proportional to $\sum_q = u,d,s,c$ $\bar{q}q_{V-A}$ and it gives only $\Delta I = 0$ operator. Finally, Fig. 1(d), the electroweak penguin, gives both $\Delta I = 0$, and $\Delta I = 1$ operators.

Now we consider the isospin properties of the up tree, the operator which is generated by Fig. 1(a). Because it contains both $\Delta I = 0$, and $\Delta I = 1$ components, we want to separate the operator into two parts:

$$2[C_1(\mu)O^u_1 + C_2(\mu)O^u_2] = C_+(\mu)[O^u_+ - O^u_-] + C_-(\mu)[O^u_- - O^u_+]$$

$$+ C_+(\mu)[O^c_+ + O^c_-] + C_-(\mu)[O^c_- + O^c_+]$$

(11)

where $C_+ = C_2 \pm C_1$ and $O_+ = \frac{1}{2}(O_2 \pm O_1)$. Then the first two terms on the right hand side cause $\Delta I = 1$ transition and the last two terms cause $\Delta I = 0$ transition.

Next we show that the electroweak penguins, can be expressed in terms of existing operators $6, 9, 10$. Note that the standard model predicts that $C_{7,8}(m_b)$ are very small and they are negligible compared to $C_{9,10}(m_b)$. The operators
with dominant coefficients $O_9$ and $O_{10}$, for $q = u, d$, can be written as linear combinations of $O_{10}^{u,d}$ and $O_{10}^{d}$ respectively:

$$\mathcal{H}_0 = \frac{G_F}{\sqrt{2}} \left\{ \xi_u [C_+ (\mu) O^u_+ + C_- (\mu) O^u_- ] + \frac{1}{2} [\xi_t C^{EW}_+ (\mu)] \hat{O}_+ 
\right. \\
\left. + [\xi_t C_- (\mu) - \frac{1}{2} \xi_t C^{EW}_- (\mu)] \hat{O}_- - \xi_i \sum_{i=3}^6 C_i (\mu) O_i \right\} \\
\mathcal{H}_1 = \frac{G_F}{\sqrt{2}} \left\{ [\xi_u C_+ (\mu) - \frac{3}{2} \xi_t C^{EW}_+ (\mu)] \hat{O}_+ + [\xi_u C_- (\mu) - \frac{3}{2} \xi_t C^{EW}_- (\mu)] \hat{O}_- \right\}$$

(12)

where $\mathcal{H}_1$ denotes the Hamiltonian which transforms as isospin I. The operators above are defined as:

$$\hat{O}_\pm = \frac{1}{2} (O_-^\pm - O_+^\pm), \quad \hat{O}_\mp = \frac{1}{2} (O_-^\pm + O_+^\pm), \quad C^{EW}_\pm = C_{10} \pm C_9.$$

In studying $B \to K \pi$ and $\pi\pi$ decays, it is important to classify final states in terms of strong interaction eigenstates, i.e. isospin states. This will allow us to take in to account of all rescattering effects which have been discussed extensively in the literature.

$$A_B = B_2^+ \to \pi^K_0 = B_2^+ + A_2^+ + A_2^- = P + A - \frac{1}{3} P^W_3$$

$$-\sqrt{2} A_B = B_2^0 \to \pi^0 K^0 = B_2^+ + A_2^+ - 2A_2^- = P + T + C + A + \frac{2}{3} P^W_3 + P^W_1$$

$$A_B = B_2^0 \to \pi^0 K^0 = B_2^- - A_2^- - A_2^+ = P + T + \frac{1}{3} P^W_3$$

where $A_I = \langle (K\pi)_I | \mathcal{H}_1 | B \rangle$ and $B_I = \langle (K\pi)_{\frac{1}{2}} | \mathcal{H}_0 | B \rangle$. We have also given the decay amplitudes in terms of amplitudes classified by Feynman graph structure: tree graph (T), color suppressed tree graph (C), annihilation graph (A), penguin graph (P), electroweak penguin graph ($P^W_3$), and color suppressed electroweak penguin graph ($P^W_3$).

These decays together with their charge conjugate version constitute 8 physical observables. Unlike $K \to \pi\pi$ decays Watson’s theorem cannot be applied, and we cannot say much about final state interaction phases for these amplitudes. We thus write:

$$A_i = a_i e^{i\alpha_i} + b_i e^{i(\beta_i + \phi_i)} \quad i = 1, 2, 3.$$

(13)

Here we separate the contributions which are proportional to $\xi_u \equiv |\xi_u| e^{i\phi_3}$ from those proportional to $\xi_c$ and $\xi_t$. $\alpha_i$ and $\beta_i$ are final state strong interaction
phases. It is trivial to write $a_i$ and $b_i$ in terms of matrix elements of the effective Hamiltonian Eq. (12). Note that there are 12 independent parameters in Eq. (13), and only 8 decay rates for $B \to K\pi$.

In terms of matrix elements of the Hamiltonian, we have

$$B_+ = P_1; \quad A_\pm = \tilde{C}_+ Q_\pm^2 + \tilde{C}_- Q_\pm^2; \quad A_\mp = \tilde{C}_+ Q_\mp^2 + \tilde{C}_- Q_\mp^2,$$  \hspace{1cm} (14)

where

$$\tilde{C}_\pm = \xi u C_{\pm} - \frac{3}{2} \xi t C_{\pm}^{EW} = |\xi u| C_{\pm}(e^{i\phi_3} - \delta_\pm),$$  \hspace{1cm} (15)

and $\tilde{Q}_I^I$ is an appropriate matrix element $\langle (K\pi)_I | \tilde{O}_I | B \rangle$. We also record

$$P = \tilde{C}_+ Q_+^2 + \tilde{C}_- Q_-^2 + \xi_c [C_+ Q_c^c + C_- Q_c^-] + \xi_t \sum_{i=3}^6 C_i Q_i,$$  \hspace{1cm} (16)

where

$$\tilde{C}_\pm = |\xi u| C_{\pm}(e^{i\phi_3} - \frac{1}{3} \delta_\pm), \quad \tilde{Q}_\pm^I = \langle (K\pi)_I | \tilde{O}_I | B \rangle, \quad \text{and} \quad Q_c^c = \langle (K\pi)_c | \tilde{O}_c | B \rangle.$$

So far, we have been quite general. Now, we shall go on to discuss the hadronic matrix elements. What do we know about these matrix elements? Over the years, we have learned quite a bit. In particular, we have learned that classifying operators in terms of their topology, $A$, $C$, $T$, $P$, etc., gives us fairly accurate intuition in guessing the size of the matrix elements. For example, we guess that $A$, the annihilation graph, should be quite small compared to $T$ because it is suppressed by the small probability that the spectator quark and $b$ quark come within the range so that they can annihilate. Similarly, $C$ is suppressed compared to $T$ because of the color factor. These statements imply definite relationships between hadronic matrix elements which appear in Eq. (14). These relations should be checked experimentally. But, for the time being, we shall proceed and ask if these conventional wisdom would allow us to determine $\phi_3$, the KM phase. The first simplification is $A(B^+ \to \pi^+ K^0) = B_\frac{1}{2} + A_\frac{1}{2} + A\frac{3}{2} \approx |P|e^{i\phi_P}$ if $A$ and $P_{EW}$ is negligible compared to $P$. The second simplification is that $\tilde{Q}_-$ transforms like a $\Delta I = 0$ operator in the limit of $U$ spin symmetry. So, $\tilde{Q}_-^2$ vanishes in the SU(3) limit and is proportional to SU(3) breaking interaction. For our purpose, we neglect it. Then $-3A_\frac{3}{2} = |P|\xi_{3/2}e^{i\phi/2}(e^{i\phi_3} - \delta_+)$, where $|P|\xi_{3/2} = -3|\xi u| C_+ Q_+^2$. These considerations make analysis of $B^+ \to K^+ \pi^0$ simple:

$$-\sqrt{2}A(B^+ \to K^+ \pi^0) = A(B^+ \to K^0 \pi^+) - 3A_\frac{3}{2},$$  \hspace{1cm} (17)
Neubert considers
\[ R_4^{-1} = \frac{2[\text{Br}(B^+ \to K^+\pi^0) + \text{Br}(B^- \to K^-\pi^0)]}{\text{Br}(B^+ \to K^0\pi^+) + \text{Br}(B^- \to K^0\pi^-)} = 1-2\epsilon_{3/2}\cos \Delta \phi (\cos \phi_3 - \delta_+) \] (18)

where \( \Delta \phi = \phi_3 - \phi_P \). Fleischer considers
\[ R = \frac{[\text{Br}(B^0 \to K^+\pi^-) + \text{Br}(B^0 \to K^-\pi^+)]}{\text{Br}(B^+ \to K^0\pi^+) + \text{Br}(B^- \to K^0\pi^-)} \] (19)

The decay \( B^0 \to K^+\pi^- \) is bit more complicated because we have to confront the contribution from \( A_4 \). It involves two complex amplitudes. He suplements the complexity by also considering
\[ A_0 = \frac{\text{Br}(B^0 \to K^+\pi^-) - \text{Br}(B^0 \to K^-\pi^+)}{\text{Br}(B^+ \to K^0\pi^+) + \text{Br}(B^- \to K^0\pi^-)} \] (20)

Detailed numerical analysis indicates that both of these methods are useful for determining \( \phi_3 \). In this discussion, I had to simplify the problem in order to present the essence. I refer the reader to the original contribution for complete analysis. It is clear that their contributions lead to much progress but much more work is necessary along this direction. For example, only subset of \( B \to K \pi \) has been considered. There are 8 of them altogether!

5 SUSY in B and K decays

Predictions of the minimal supersymmetric theories (MSSM) is essentially same as those of the SM. If nature has chosen MSSM, we will not learn anything new from experiments on \( B \) and \( K \) decays. We should not be too discouraged by this though, as it is likely that she has chosen a theory which is more elegant than the MSSM. But, as long as we can not specify which theory nature has chosen, it is not an easy task to analyze its predictions. There are as many as 124 parameters in a non-minimal SUSY, and perhaps even more. Because \( B \) and \( K \) decays give stringent restrictions on flavor changing neutral current strengths, we shall focus general predictions of FCNC processes of a non-minimal SUSY - mostly penguin effects.

In SUSY, there is a bosonic partner for each helicity of a quark. Here we begin by examining a \( 6 \times 6 \) squark mass matrix of the MSSM.

\[
\tilde{M}_D^2 = \begin{pmatrix}
\tilde{M}_{D_{LLL}}^{\text{tree}}\tilde{M}_{D_{LLL}}^{\text{tree}†} + c_1 M_U M_U^† & A m_{3/2} M_D (1 + \frac{\alpha_s}{\sqrt{6}} M_U M_U^†) \\
A^* m_{3/2} (1 + \frac{\alpha_s}{\sqrt{6}} M_U M_U^†), M_D^† & \tilde{M}_{D_{RR}}^{\text{tree}†}\tilde{M}_{D_{RR}}^{\text{tree}}
\end{pmatrix}
\] (21)
where
\[
\tilde{M}^2_{DLL} = \left( m_3^2/2 + (v_1^2 - v_2^2) \left( \frac{g'^2}{12} - \frac{g^2}{4} \right) \right) 1 + (M_D^{\text{diag}})^2
\]
\[
\tilde{M}^2_{DRR} = \left( m_3^2/2 + (v_1^2 - v_2^2) \frac{g'^2}{6} \right) 1 + (M_D^{\text{diag}})^2
\]
\[
\tilde{M}^2_{DLR} = \left( |A| m_3^2/2 + \mu \frac{v_1}{v_2} \right) M_D^{\text{diag}}.
\]

\[\text{(22)}\]

1 is a 2 × 2 unit matrix, \(M_D,(U)\) is a mass matrix of a \(D(U)\) quark, and \(M_D^{\text{diag}}\) is a corresponding diagonalized matrix. Note that there new FCNC effects from additional flavor mixing among squarks. Others are standard MSSM parameters. To go from MSSM to a more general theory, let us identify
\[
\Delta^2_{LL} = c_1 M_U M_U^\dagger
\]
\[
\Delta^2_{LR} = A m_3/2 M_D \left( 1 + \frac{c_2}{M_W^2} M_U^\dagger M_U \right)
\]
\[
\Delta^2_{RL} = A^* m_3/2 \left( 1 + \frac{c_2}{M_W^2} M_U^\dagger M_U \right) M_D^\dagger.
\]

and generalize \(\delta_{LL} = \frac{\Delta_{LL}}{\tilde{m}}\), \(\delta_{LR} = \frac{\Delta_{LR}}{\tilde{m}}\), \(\delta_{RL} = \frac{\Delta_{RL}}{\tilde{m}}\), and \(\delta_{RR} = \frac{\Delta_{RR}}{\tilde{m}}\), where \(\tilde{m}\) is an average squark mass, as new arbitrary dimensionless parameters. We then study experimental constraints on \(\delta\) ignoring all theoretical prejudice.

This analysis has been discussed in detail by Masiero. Bounds on \(\delta\) has been obtained from experimental information on various FCNC processes. For an average squark mass and gluino mass of 500 GeV, the bounds on \(\delta\) ranges from \(10^{-1}\) to \(10^{-3}\). It could be noted that the neutron edm gives a bound of \(\text{Im} (\delta_{LR})_{11} \sim 10^{-6}\) and it is natural to assume that other components of \(\delta\) are of the same order of magnitude. If this is the case, it may be difficult of SUSY effects to show up in B and K decays.

6 B decays to \(\eta K(K^*), \eta' K(K^*), \text{ and } \eta' X_s\)

CLEO has observed
\[
\text{Br}(B \to \eta' K^+) = \left( 6.5^{+1.5}_{-1.4} \pm 0.9 \right) \times 10^{-5},
\]
\[
\text{Br}(B \to \eta' K^0) = \left( 4.7^{+2.7}_{-2.0} \pm 0.9 \right) \times 10^{-5}.
\]

\[\text{(24)}\]
These branching ratios are surprisingly large. Du has presented a review of work in progress to understand these large branching ratios. It is likely that these branching ratio is large because of gluonic content of $\eta'$. Among various suggestions, a particularly interesting one is that of Soni and Atwood. They attempt to compute $\eta' \rightarrow \text{glue glue}$ by considering triangle anomaly\textsuperscript{14}. They then estimate $b \rightarrow \eta' \text{gluon}$. We should note, however, that major contribution to this decay comes from off shell gluon. Thus the validity of the anomaly calculation is questionable at best. A universal characteristic of all the work presented by Du is that each author picks up their favorite diagram and estimates its contribution. Nature does not work this way. They have to consider all possible diagrams and sum them up. Clearly global analysis is urgently needed. Also, there are large amount of data on the gluonic content of $\eta'$. Such global analysis must be consistent with the previously known properties of $\eta'$.

7 A new calculation for direct CP violation: $\epsilon'$

Ever since the discovery of CP violation, experimentalists have been looking for an evidence of direct CP violation. Now that the result of NA31 has been confirmed by E832, the direct CP violation has been experimentally established.

The challenge for theorists is to extract physics from the new value of $\epsilon'$. This is not an easy task. Before we compute CP violating amplitudes for $K \rightarrow \pi \pi$ decay, we have to demonstrate that we understand CP conserving decay amplitudes. This means that we need to understand the $\Delta I = \frac{1}{2}$ rule. At the moment there is no clear understanding of this rule. So, one choice is to obtain hadronic matrix elements from data\textsuperscript{15}. If the $\Delta I = \frac{1}{2}$ rule is due to some new physics, this procedure will miss the new physics. Clearly, this is not satisfactory. We want to compute everything from basic principles. The approach taken by Paschos is an attempt along this direction.

Let us start from the defining equation:

$$\epsilon' = e^{i(\delta_2 - \delta_0)} \frac{1}{2\sqrt{2}} \omega \left( \frac{A_0}{A_0} - \frac{A_2}{A_2} \right).$$ \hspace{1cm} (25)$$

where $A_I = \langle (\pi \pi)_I | \mathcal{H} | K \rangle$ and $\omega = |A_2/A_0| \sim .05$ and $\delta_I$ is the $\pi \pi$ phase shift for isospin $I$ channel.

In terms of operators in the effective Hamiltonian $\mathcal{H}$,\n
$$\frac{\epsilon'}{\epsilon} = -i e^{i(\delta_2 - \delta_0)} \times 10^{-4} \left( \frac{\text{Im} \tau}{10^{-7}} \right) r \left( \sum_i y_i \langle Q_i \rangle_0 - \frac{1}{\omega} \sum_i y_i \langle Q_i \rangle_2 \right)$$ \hspace{1cm} (26)$$

where $y_i$ are the quark coupling constants and $r$ is a ratio of the quark masses.
where \( r = \frac{G_F \omega}{2|\text{Re } A_0|} = 336 \, \text{GeV}^{-3} \); \( y_i \) is the imaginary part of Wilson coefficients; \( \langle Q_i \rangle_f \) is a hadronic matrix element \( \langle (\pi \pi)_I | 0_i | K \rangle \); \( \tau = \frac{V^*_{ts} V_{td}}{V^*_{us} V_{ud}} \).

In this workshop, Paschos described computation of hadronic matrix elements \( \langle Q_i \rangle_f \) based on the \( \frac{1}{N_C} \) expansion. They have obtained

\[
5 \times 10^{-4} \leq \frac{\epsilon'}{\epsilon} \leq 22 \times 10^{-4} \tag{27}
\]

for \( m_s = (150 \sim 175) \text{MeV} \). Their prediction increases if smaller values of \( m_s \) is taken.

This is an on going study and much more work remains: (I) The Wilson coefficients can be computed reliably only at some large energy scale \( \Lambda_c \). But hadronic matrix elements can be computed only at low energy scale. So, there has to be some compromise. They have chosen \( \Lambda_c \sim 800 \text{MeV} \). Wilson coefficient functions have large scale dependence in this region. When the coefficient functions and hadronic matrix elements are combined, the result for \( \frac{\epsilon'}{\epsilon} \) should not have the scale dependence. This has to be studied carefully. (II) It is necessary to demonstrate that \( K \rightarrow \pi \pi \) decay can be understood in this framework. Indeed, their result for \( K^+ \rightarrow \pi^+ \pi^0 \) decay, the \( \Delta I = \frac{1}{2} \) channel, is consistent with experiment. But it is necessary to understand the \( \Delta I = \frac{1}{2} \) amplitude. Personally, I am skeptical toward a claim that the \( \Delta I = \frac{1}{2} \) rule can be understood within the frame work of \( \frac{1}{N_C} \) expansion.

8 Summary

We have tried to have extended discussions on penguins. We tried to understand how we might extract \( \phi_2 \) and \( \phi_3 \) from data. We don’t think there is one best method to extract these angles. It is an experiment driven field, and time will tell. We tried to understand \( \frac{\epsilon'}{\epsilon} \) from basic principles of the SM. There is much more work to be done along this direction. We tried to understand \( B \rightarrow \eta' + X \) decays. This also requires more work. Seeing effects of SUSY in \( B \) and \( K \) decays is an exciting possibility. We have to keep on searching.

Acknowledgements

This work has been supported in part by Grant-in-Aid for Special Project Research (Physics of \( \text{CP} \) violation). Comments from J. L. Rosner was helpful in finalizing the manuscript. I wish to express my gratitude to the organizers, C. A. Dominguez and R. D. Viollier for their effort in organizing the workshop, and for their hospitality.
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