Theoretical Studies of Flavor-Changing Neutral Currents in 1980's

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I. A little (biased) history of flavor physics mainly in 1980's

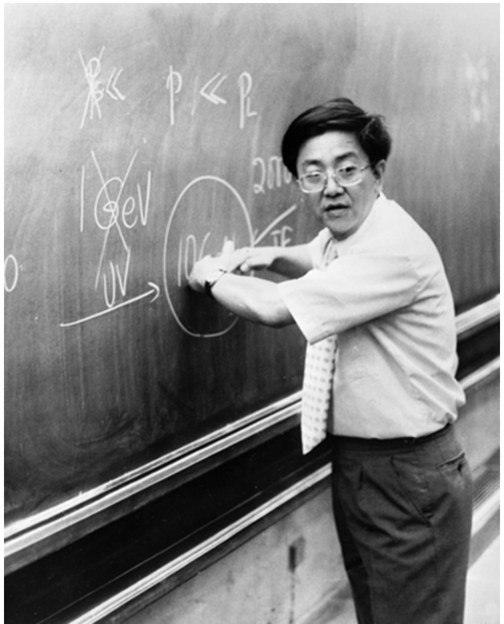
If there is a perfect symmetry among generations (or flavors), generation number or flavor is exactly conserved (← Noether). Thus Flavor-Changing Neutral Current (FCNC) stems from the violation of flavor symmetry .

The Weinberg-Salam model with only 3 favors breaks the symmetry, and to remedy the problem of too large FCNC c quark was introduces (GIM).

FCNC is sensitive to the breaking of the flavor symmetry due to the mass-squared differences among quarks.

<u>M. Gaillard and B.W. Lee</u> ('74)

They could predict $m_c \simeq 1.5(\mathrm{GeV})$
before the discovery of J/Ψ :
ideal work in the field of phenomenology.
(Their work greatly influenced ours.)



How about t quark introduced by Kobayashi and Maskawa ?

In 80's t quark was regarded to be not so heavy, $m_t \leq 30$ (GeV) .
The formula by Gaillard-Lee , using the approximation $m_q \ll M_W$, still seems to give reasonable results for FCNC.

However, **Takeo Inami** (Chuo Univ.) and C.S. L. published a paper ("Effects of Superheavy Quarks and Leptons in Low-Energy Weak Processes $K_L \to \mu\bar{\mu}$, $K^+ \to \pi^+\nu\bar{\nu}$ and $K^0 \leftrightarrow \bar{K}^0$ ", Prog. Theor. Phys. 65 ('81) 297).

In contrast to the common sense, we assumed the presence of "arbitrarily" heavy (but not so heavy as to spoil perturbation) intermediate quarks and leptons (t, t', L). We derived several functions describing the quantum effects of these heavy fermions to the FCNC processes, without invoking to the approximation $m_q \ll M_W$.

A strong theoretical motivation

We were interested in the possible **non-decoupling effects** of heavy fermions, anticipated from the **large Yukawa couplings** of heavy fermions in the theories with **spontaneous symmetry breaking** (SSB) .

(Purpose) : to make clear **whether the quantum effects due to the heavy fermions really give some non-decoupling effects or not**.

Eventually, it turned out $m_t \simeq 175$ (GeV) $> M_W$
$\rightarrow$ We were lucky.

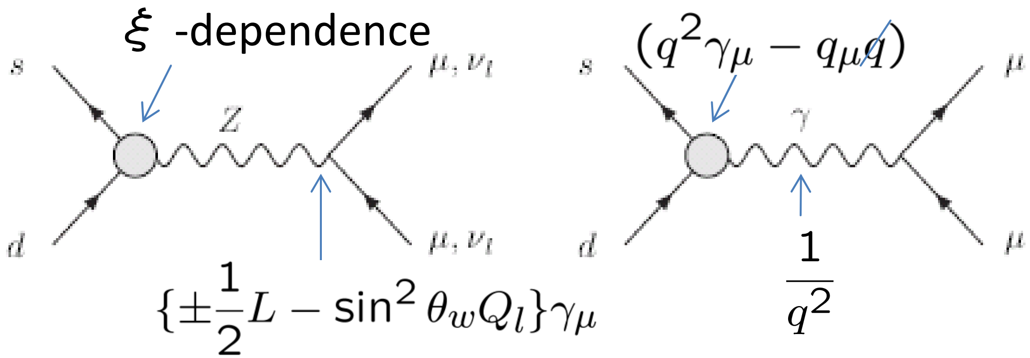
R_ξ gauge (K. Fujikawa, B.W. Lee and A.I. Sanda, Phys. Rev. D6('72) 2923)

Each diagram has ξ - dependence, but the final result should be ξ - independent. A good check of calculation.

In this gauge, the (would-be) Nambu-Goldstone boson has **Yukawa couplings, which are proportional to masses of intermediate heavy fermions** $\rightarrow$ the **possibility of non-decoupling effects of heavy fermions**

A very useful suggestion by K. Fujikawa

The ξ -dependence appearing in the FCNC Z-vertex gave ξ - dependent 4 fermi effective lagrangian with vector-like coupling of charged lepton:



The problem seemed to be solved by adding "QED-penguin" diagram, though the penguin diagram has no contribution to the decay processes $K_L \to \mu\bar{\mu}$, $K^+ \to \pi^+\nu\bar{\nu}$
I asked Prof. Fujikawa his advise and he recommended me to calculate the $\bar{s}d\gamma$ vertex as well.

The calculated $\bar{s}d\gamma$ vertex was later used in the analysis of FCNC radiative decays, e.g. $b \to s\gamma$

We greatly appreciate the useful advice.

Attempts to estimate m_t

Is it possible to estimate m_t by comparing with the data on the FCNC processes ?

A.J. Buras attempted to estimate m_t

(“An Upper Bound on the Top Quark Mass from Rare Processes”, Phys. Rev. Lett. 46(‘81) 1354)

Because of large uncertainty of mixing angles, CP phase at that time made the estimation difficult.

We thank Prof. Buras very much for bringing public attention to our work.

2. Non-decoupling effects due to heavy fermions

There is a ``decoupling theorem” (T. Appelquist and J. Carazzone (‘75)), saying that the effects of heavy (unknown) particles are suppressed by the inverse powers of their large masses.

@ tree level

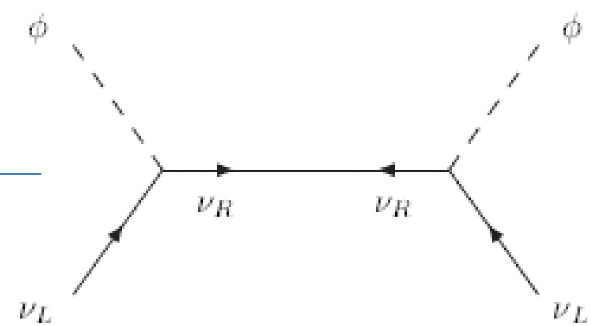
An example: see-saw mechanism” (Gell-Mann, Ramond & Slansky, T. Yanagida) :

$$m_L \simeq \frac{m_D^2}{m_R} \quad (m_R : \text{Majorana mass of } \nu_R)$$

The Majorana mass term for the left-handed neutrino does not exist as a renormalizable operator in the theory and is described in terms of gauge invariant operator with higher mass dimension (> 4),

$$\propto \frac{1}{m_R}(\phi^\dagger L)^2$$

$(\phi, L :$ Higgs and lepton doublets$)$



m_R : reflects the scale of unknown new physics (NP)

$m_R \gg M_W \quad \rightarrow$ decoupling

@ quantum level
The decoupling is not so trivial , as the energy of intermediate states can be large. In fact, in QED assumed heavy lepton with mass M does contribute to the renormalization factor, as $\log(\frac{\Lambda}{M})$ (Λ : cutoff)

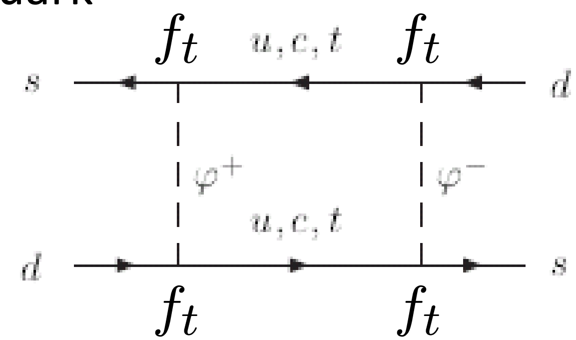
After the renormalization, all remaining observables (described by operators with higher mass dimensions) are suppressed by the powers of 1/M

In gauge theories with spontaneous symmetry breaking (SSB), however, **the situation can be quite different.**
The large masses of heavy particles are provided not by some New Physics (NP) mass scale M, but from the weak scale M_W itself, or the VEV of Higgs.
: **no suppression like 1/M**
Since every masses come form the VEV, heavy means “strong” Yukawa coupling. → **We can expect some non-decoupling effects**

In fact, in our work (‘81), we found non-decoupling effects of heavy fermion, say t quark, in FCNC processes, growing as

$$\sim m_t^2 \quad \text{or} \quad \log(\frac{m_t}{m_{u,c}})$$

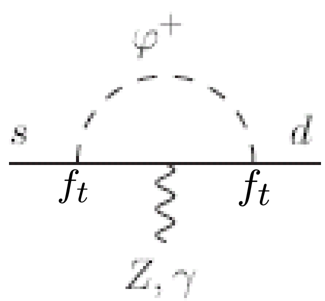
For instance, in the box diagram, the exchange of N-G boson $\varphi^{\pm}$ and t quark



$$\rightarrow \quad f_t^4 \frac{1}{m_t^2} = (g\frac{m_t}{M_W})^4 \frac{1}{m_t^2} = g^4 \frac{m_t^2}{M_W^4} \quad (m_t \gg M_W)$$

$$(E(x_t) \simeq -\frac{1}{4} x_t \text{ for } x_t \gg 1 \quad (x_t \equiv \frac{m_t^2}{M_W^2}))$$

Qualitative difference between Z and γ vertices



Z vertex: $g f_t^2 = g^3 \frac{m_t^2}{M_W^2} \quad (C(x_t) \simeq \frac{1}{4} x_t \text{ for } x_t \gg 1)$

γ Vertex: $e(q^2\gamma_\mu - q_\mu q)\, f_t^2 \frac{1}{m_t^2} \log m_t = e g^2 \log m_t$

↑ CVC

To some extent, the γ vertex mimics QED, where decoupling theorem holds.
$\longrightarrow$ The contribution of 4th generation, if it ever exists, may be remarkable in the Z vertex (weak-penguin diagram).

3. CP violation in the Kobayashi-Maskawa model and the non-decoupling effects

It was great news that the Nobel prize in physics of 2008 was awarded to Professors Nambu, Kobayashi and Maskawa.

In the **Kobayashi-Maskawa (KM) model**, CP violation is accompanied by the breaking of flavor symmetry. Namely, if there is mass degeneracy between different generations, CP violation is known to disappear even for non-vanishing CP phase. Intuitively, in this case the number of generations is effectively reduced from 3 to 2.

→ **CP violating observables are induced through FCNC processes**

To get CP violation in the KM model, all of three generations have to participate. In fact, in the neutral kaon system CP violating observable ϵ_k is dominated by the non-decoupling effect due to t quark :

$$\epsilon_k \propto \mathrm{Im}\{(V_{ts}^* V_{td})^2\}\ E(x_t) \propto \mathrm{Im}\{(V_{ts}^* V_{td})^2\}\frac{m_t^2}{M_W^2}$$

As far as all three generations participate, CP violation should happen everywhere, in particular in the B meson system.

In addition, since the non-decoupling effect due to the top quark is the dominant source, such CP violating effect is expected to be large in the B system , which couples to the t quark more directly (A.I. Sanda et al.)
→ B-factory experiment

4. The ideas of NP and the non-decoupling effects

"Puzzles "

(1) Rather large rate of $D^0 \leftrightarrow \bar{D}^0$ mixing

$$x_D \equiv \frac{\Delta M_D}{\Gamma_D} = (0.811 \pm 0.334) \cdot 10^{-2} \quad \text{(HFAG)}$$

, while the short distance contribution of the Standard Model is estimated to be very small due to small mass-squared differences among d, s, b quarks,

$$x_D(SD) \sim 10^{-6} - 10^{-4}$$

(2)Possible deviation from the Standard Model predictions for CP asymmetries in B decays (e.g., A. Soni et al., arXiv: 0807.1971[hep-ph])

- $\sin 2\beta$ predicted by use of ϵ_k and $\frac{\Delta M_s}{\Delta M_d}$ is a little larger than directly measured value by $B \to \psi K_S$
- Rather large difference in the direct CP asymmetry,

$$\Delta A_{CP} = A_{CP}(B^- \to K^-\pi^0) - A_{CP}(B^0 \to K^-\pi^+) = (14.4 \pm 2.9)\%$$

- Indication of large non-standard CP phase in the B_s decay, $B_s \to \psi\phi$

Among various possibilities of NP, the presence of fourth family may be a natural cause of these puzzles.

Since the heavy fermions of fourth generation should get their masses through SSB, they yield non-decoupling effects enhanced as $m_{t'}^2/m_t^2$, compared with those by third generation, except for the factors of generation mixings.

The enhancements by the powers of $m_{t'}^2$ will be realized in the box diagram and FCNC Z-vertex (weak penguin), thus making the characteristic predictions of this scenario possible.

5. Summary

(1) The question of whether heavy fermions decouple from low energy processes or not was an interesting theoretical issue in early 80's.

(2) The top quark turned out to be unexpectedly heavy, and was found to have important non-decoupling contributions to FCNC processes, including CP violating processes, as the reflection of SSB.

(3) The extent of the non-decoupling effects is different , e.g. between QED- and weak-penguin diagrams.

(4) In the Kobayashi-Maskawa model, CP violating observables are inevitably induced by FCNC processes.

(5) The non-decoupling effects of the top quark play crucial roles in the CP violating observables both in K and B meson systems.

(6) Recent claims on the possible deviations from the Standard Model predictions concerning $D^0 \leftrightarrow \bar{D}^0$ and CP asymmetries in B decay processes, may signal some New Physics (NP).

(7) If we take the possibility of the 4th generation as NP, the unknown heavy fermions are expected to have enhancement factor, such as $m_{t'}^2$.

(8) The fact that the enhancement is remarkable in the box and weak-penguin diagrams, make the characteristic predictions of the 4th generation scenario possible.