$K^o-\overline{K^o}$ MIXING: APPROACHING ITS SHORT-DISTANCE ORIGIN AND HEAVY FLAVOURS THROUGH LOOPS

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There have been three "mysteries" in the history of the K-meson system: two of the pre-1964 physics as summarized by Feynman[1)],

|1| the unknown reasons for strangeness,

|2| the unknown inner machinery of the $K^o-\overline{K^o}$ mixing,

and the third, revealed to us in 1964[2)],

|3| CP violation.

The attempts to explain these puzzles have been crucial in building the present, standard-model (SM) picture for understanding of elementary particle physics. As regards the first two points, I first want to illustrate how their study has opened the door to heavy flavours. Then I shall focus on some recently proposed short-distance $K^o-\overline{K^o}$ mixing mechanisms, and also remind the reader of the problem of separating short-distance (SD) from long-distance (LD) effects. As for CP violation |3|, it is often considered to be just on the border of the SM. The observation of CP violation, still restricted to the K^o meson, makes it that the $K^o-\overline{K^o}$ system is still one of the most intriguing systems in nature. The increasing body of data from heavy-quark physics have a chance to move the kaon from such a "strange" (if not distinguished) place, and to provide a valuable test of the SM.

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1. From strangeness to heavy flavours:

Three, four, ... or even more generations

The strange behaviour discovered in the accelerator experiments in the fifties (strange particles are produced in large numbers , but their decay into non-strange hadrons proceeds slowly) has found an explanation in the quark picture of hadrons. There is a strange flavour (s-) quark appearing in a strange hadron. The conservation of the strangeness quantum number[3] is reduced to flavour conservation in strong interactions, while weak decays involve strangeness-changing currents, constructed by the Cabibbo[4] doublet

$$\binom{u}{d'} ; \quad d' = \cos\theta_C d + \sin\theta_C s \ . \tag{1a}$$

At the same time, the lack of strangeness-changing weak neutral currents warned physicists to expect a new quark flavour - charm (c)[5], entering a new doublet

$$\binom{c}{s'} ; \quad s' = -\sin\theta_C d + \cos\theta_C s \ . \tag{1b}$$

In this way, the weak neutral current is completed to

$$(\bar{u},\bar{d}')\tau_3\binom{u}{d'} + (\bar{c},\bar{s}')\tau_3\binom{c}{s'} \ ,$$

the unwanted $\bar{d}s$ and $\bar{s}d$ couplings cancel and the Z^o boson couples diagonally in flavour. This represents the so-called GIM cancellation at the three level. The perspicacious prediction of charm was proved to be correct in the discovery of J/ψ [6], and opened the door to the world of heavy flavours. Indeed, after the discovery of the τ lepton[7], another quark doublet was required. The bottom (b-) quark was confirmed by the discovery of Υ (upsilon) resonances[8], and the top (t-) quark seems to be almost established[9]. Thus, we end up with 12 fermions distributed into 3 generations in the standard Glashow-Salam-Weinberg (GWS) model, in the form of left-handed doublets and right-handed singlets

$$\begin{matrix} \binom{\nu_e}{e}_L, \binom{u}{d'}_L & \binom{\nu_\mu}{\mu}_L, \binom{c}{s'}_L & \binom{\nu_\tau}{\tau}_L, \binom{t}{b'}_L \\ e_R, u_R, d_R & \mu_R, c_R, s_R & \tau_R, t_R, b_R \end{matrix} \ . \tag{2}$$

Here, the states seen by the weak interaction (d', s', b') are connected with the mass eigenstates (d, s, b) by the unitary Kobayashi-Maskawa[10] matrix, V_{KM}:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{KM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}, \quad V_{KM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \tag{3}$$

$$\begin{pmatrix} c_1 & s_1c_3 & s_1s_3 \\ -s_1c_2 & c_1c_2c_3-s_2s_3e^{i\delta} & c_1c_2s_3+s_2c_3e^{i\delta} \\ s_1s_2 & -c_1s_2c_3-c_2s_3e^{i\delta} & -c_1s_2s_3+c_2c_3e^{i\delta} \end{pmatrix}.$$

Here, $c_i = \cos\theta_i$, $s_i = \sin\theta_i$, where θ_i represent three rotational angles, and the phase δ enables us to accommodate CP violation in the model with three generations. The ultimate source of this CP-violating phase δ in the standard model is arbitrary Higgs-Yukawa couplings. Generally, for n generations there are $(n-1)^2$ parameters left in V_{KM}:

$$\begin{aligned} &\frac{n}{2}(n-1) \text{ real rotational angles and} \\ &\frac{1}{2}(n-1)(n-2) \text{ arbitrary physical phases.} \end{aligned} \tag{4}$$

The unique complex phase δ in (3) provides the single (K-M) mechanism of CP violation in the minimal SM. If there is the fourth generation, one has three CP-violation parameters instead.

2. Loop diagrams for the K^o-$\overline{K^o}$ mixing

2.1. Standard box-diagram and the charm quark mass

The strong interaction eigenstates $K^o(S = -1)$ and $\overline{K^o}(S = 1)$ have been expected to mix[11] due to the weak interaction. The resulting removal of degeneracy, the K_L-K_S mass difference

$$\Delta m^{Expt.} = (0.5349 \pm 0.0022) \times 10^{10} \hbar\, sec^{-1} \simeq 3.5 \times 10^{-15} \text{ GeV}, \tag{5}$$

is extremely tiny. This indicates that the effective $\Delta S = 2$ interaction (Fig. 1) producing the mass difference via

$$\Delta m_K \simeq \frac{1}{m_K} \langle K^o | H_{eff}^{\Delta S=2} | \overline{K^o} \rangle = 2 \text{ Re } M_{12} \tag{6}$$

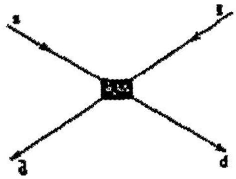

Fig.1. Effective $\Delta S=2$ transition at the quark level.

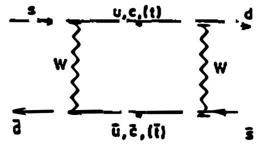

Fig.2. Simplest SD K^0-$\overline{K^0}$ mixing mechanism representing the "black box" of Fig.1.

must be of higher order in G_F. Indeed, the SM provides only the $\Delta S=1$ lowest-order interaction of the form

$$\frac{g}{\sqrt{2}}\Big[\bar{s}\gamma^\mu L(u\sin\theta_C + c\cos\theta_C)W_\mu + \bar{d}\gamma^\mu L(u\cos\theta_C - c\sin\theta_C)W + \text{h.c.}\Big];\quad L=\frac{1-\gamma_5}{2}\,. \tag{7}$$

Replacing the black box of Fig. 1 by the box diagram of Fig. 2 led Gaillard and Lee[12)] to the result

$$H^{\Delta S=2}_{Box} = \frac{G_F^2}{16\pi^2}\,(m_c^2 - m_u^2)\cos^2\theta_C\,\sin^2\theta_C\;O^{\Delta S=2}\,, \tag{8a}$$

where

$$O^{\Delta S=2} \equiv \bar{d}_\alpha\gamma^\mu(1-\gamma_5)s_\alpha\,\bar{d}_\beta\gamma^\mu(1-\gamma_5)s_\beta \tag{8b}$$

represents the local 4-quark operator. The expression (8a) exhibiting the GIM calcellation at the one-loop level, played an important role in predicting the charmed quark. In fact, calculating the matrix element of the operator (8b) in the vacuum-saturation approximation (inserting a vacuum state between all possible pairs of quark fields), one obtains

$$\langle K^0|O^{\Delta S=2}|\overline{K^0}\rangle_{VSA} = \frac{8}{3}\,f_K^2 m_K^2\;;\; f_K = 1.23\, m_\pi\;\;. \tag{9a}$$

This gives

$$(\Delta m_K^{Box})_{VSA} = \frac{G_F^2}{6\pi^2}\cos^2\theta_C\,\sin^2\theta_C\,f_K^2 m_K m_c^2\;, \tag{10a}$$

which, matched to the measured value (5), predicts the light c-quark of the order of 1 GeV.

There are some steps by which the calculation of Δm_K^{Box} could be improved:

(a) the VSA can be corrected by the "B parameter" (to which we shall refer later), giving the true matrix element

$$<K^o|O^{\Delta S=2}|\overline{K^o}> = <K^o|O^{\Delta S=2}|\overline{K^o}>_{VSA} \times B \ , \tag{9b}$$

and consequently

$$\Delta m_K^{Box} = B \times (\Delta m_K^{Box})_{VSA} \ . \tag{10b}$$

(b) Including the third generation[13] (i.e. the t quark in the loop of Fig. 2) invokes the K-M factors

$$\lambda_q \equiv V^*_{qd}V_{qs} \ , \text{ constrained by} \\ \lambda_u + \lambda_c + \lambda_t = 0 \ , \tag{11}$$

and thus leads to an imaginary, CP-violating part in

$$H^{\Delta S=2}_{Box} = \frac{G_F^2}{16\pi^2} \left[m_c^2\lambda_c^2 + \frac{2\lambda_c\lambda_t}{1-m_c^2/m_t^2} \ln \frac{m_t^2}{m_c^2} + m_t^2\lambda_t^2\right]O^{\Delta S=2} \ . \tag{12}$$

The real part of (12) is practically unaffected by the third generation.

(c) Inclusion of the QCD corrections[14] does not substantially change the box-diagram contribution to Δm_K.

Let us illustrate the overall effects of improvements (a), (b) and (c):

$$\Delta m_K^{Box} = \frac{G_F^2}{6\pi^2}\cos^2\theta_1\sin^2\theta_1 f_K^2 m_K m_c^2 B\left[\eta_1+2\eta_3 K \ln\frac{m_t^2}{m_c^2} + \eta_2 \frac{m_t^2}{m_c^2} K^2\right]; \tag{13a}$$

this is to be compared with (10a). Adopting from Ref. 15 the numerical values of QCD correction coefficients ($\eta_1 = 0.7$, $\eta_2 = 0.6$, $\eta_3 = 0.5$), the value of the K-M factor ($K = \sin^2\theta_2 + \sin\theta_2 \sin\theta_3 \cos\delta \simeq 0.0025$) and the numerical coincidence

$$\frac{G_F^2}{6\pi^2} \cos^2\theta_1\sin^2\theta_1 \ f_K^2 m_K m_c^2 \simeq \Delta m_K^{Expt.} \ ,$$

one obtains

$$\Delta m_K^{Box} = \Delta m_K^{Expt.} \ B\left[0.7 + 0.03 + 0.01\right] \ . \tag{13b}$$

The dominance of the c-quark contribution (the first term in the bracket) justifies the prediction of m_c from the box diagram. There was a suggestion of introducing another box diagram that would enable one to predict the top quark mass.[16)]

2.2. Resolution of the double-penguin controversy

Hochberg and Sachs[16)] recently argued that the double-penguin box diagram (Fig. 3a) led to the local SD lagrangian proportional to m_t^2, which enabled them to derive the bound $m_t < 45$ GeV. It has been shown in detail by Eeg and myself[17)] that such a conclusion results from an oversimplified procedure of taking (after reducing the diagram of Fig. 3a to the one of Fig. 4) the momentum-independent penguin vertex P and considering m_t as a common cut-off for double-penguin loops. The points in which we have improved the SD treatment of the double penguin are as follows:

(a) keeping the momentum dependence of the penguin loop and the "non-leading" terms;
(b) taking into account the non-local part (corresponding to $p_\mu p_\nu/p^2$ term in the penguin-gluon propagator);
(c) taking into account the full set of diagrams of Fig. 3 (the crossed diagrams avoiding an LD interpretation).

This leads to the result

$$H_{DP}^{\Delta S=2} = (-5)\ \frac{16}{3}\ \frac{G_F^2}{18(4\pi)^4}\ [\lambda_u^2 I(\mu^2,m_c^2) - 2\lambda_u\lambda_t K(\mu^2,m_t^2) + \lambda_t^2 I(m_c^2,m_t^2)]\, O^{\Delta S=2}, \qquad (14)$$

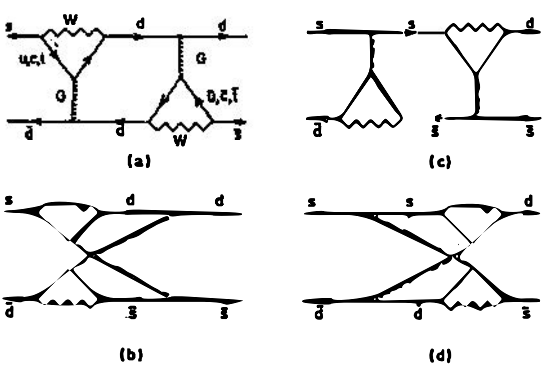

Fig.3. Double-penguin SD mechanism of the K^0-$\bar{K}^0$ mixing.

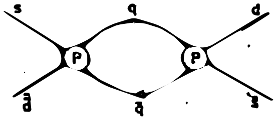

Fig.4. Double-penguin in terms of the effective penguin vertices P.

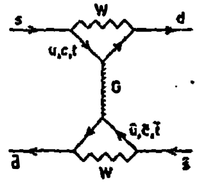

Fig.5. Siamese-penguin SD mechanism of the K^0-$\bar{K}^0$ mixing.

which is to be compared with the box expression (12). Inserting the numerical values of the loop integrals I and K and the K-M angles, the terms in the bracket in (14) are $\sim 2\times 10^{-1}$, 10^{-3} and 10^{-5}, respectively. Thus, the dominance of the loop with m_c as a cut-off is evident, in contrast to the assertion of Ref. 16 and the more recent assertion of Ref. 18. This settles "the double-penguin controversy"[19] (the difference between Refs. 16 and 18 and the statement of Ref. 20), the last one conjecturing that the special case of the double penguin, the "Siamese penguin", Fig. 5, should also be negligible). An explicit evaluation of the Siamese penguin[21] confirmed the conjecture mentioned above. To conclude, considering double penguins, we are back to the original study[22,20] of their LD bilocal $(\Delta S=1)^2$ aspect. Still, there are some other SD contributions of the penguin variety, such as a "gluon-Siamese" and a "diamond" box (Fig. 6)[23].

2.3. LD vs. SD flavour change by two-unit mixings

Besides the SD part calculated in terms of various box diagrams, the K_L-K_S mass difference Δm_K also receives the LD "dispersive" contributions

$$\Delta m_K = \Delta m_K^{SD} + \Delta m_K^{LD} . \tag{15}$$

Here, the SD part receives various contributions

$$\Delta m_K^{SD} = \Delta m_K^{Box} + \Delta m_K^{DP} + \dots , \tag{16}$$

the box contribution being parametrized (expression (10b)) by the B parameter [see Table 1],and the dots representing

TABLE 1. Estimates of the B and D parameters

Method /ref.	VSA[12]	Dispers. rel.[30]	PCAC +SU(3)[24]	MIT bag[25,26]	H.O.[26]	QCD sum rules[27]	+chiral log.[28]	Lattice[29]
B	1	(0.9,1.2)	±1/3	(−0.4,2.5)	(1,3)	(−2.5,2.5);	0.3±0.07	O(1)

Method /ref.		Dispersion relations; $\pi,\eta,\eta',\rho,\omega,2\pi$ for Refs. 30 and 31 Ref.30	Ref.31	Ref.31	only 2π for Ref.32	Rédei behaviour[33]
D	0	0.1±0.4	1.54±1.4	0.56±1.28	0.46±0.13	−0.63

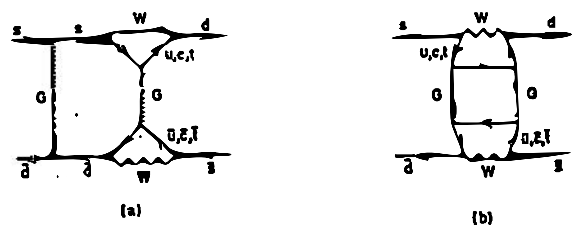

Fig. 6. Examples of new SD contributions to the K^0-$\overline{K^0}$ mixing: (a) gluo-Siamese box; (b) diamond box.

some other SD contributions[23]. The LD part of the mass difference is more difficult to calculate, and is usually parametrized as[34]

$$\Delta m_K^{LD} = D\Delta m_K \ . \tag{17}$$

There is a whole list of estimates of the D parameter [Table 1] with large uncertainties, but generally giving[35]

$$\Delta m_K^{LD} \simeq \Delta m_K^{Box} \ (\sim 10^{-15} \text{ GeV}) \ . \tag{18}$$

It is interesting to note[36] that other examples of flavour mixing lead to different results:

$$\Delta m_D^{LD} >> \Delta m_D^{Box} \ (\sim 10^{-17} \text{ GeV}), \text{ for the } D^o\text{-}\overline{D^o} \text{ mixing} \tag{19}$$

and

$$\Delta m_B^{LD} << \Delta m_B^{Box} \ (\sim 10^{-13} \text{ GeV}), \text{ for the } B^o\text{-}\overline{B^o} \text{ mixing} \ . \tag{20}$$

While the box contribution in (18) roughly conforms to the experimental value (5), the box contribution for the D-system (see (19)) is considerably smaller than the existing upper bound[37]

$$|\Delta m_D^{Expt.}| \lesssim 6\times 10^{-13} \text{ GeV} \ . \tag{21}$$

The estimated dispersive contribution[36] $\Delta m_D^{LD} \sim 10^{-15}$ GeV is much smaller than (21), and an observation of large mixing in the D^o-D^o system would signal "new physics". The beloved conservative extension of the minimal SM studied for the pseudoscalar-meson mixing is obtained by adding a fourth generation[38]. In particular, an ultraheavy quark should not exceed the charm quark contribution[39] to the standard box K^o-$\overline{K^o}$ mixing. Also, the proper treatment of the diamond box, mentioned above, has ruled out the possibility of getting the bound on m_t from Δm_K. Instead, a non-trivial bound on m_t could be placed if experimental limits on the B_s-$\overline{B_s}$ mixing[40] could be obtained (even in the presence of the fourth generation). In view of the relation (20), the B^o-B^o mixing revives the interest in a detailed knowledge of SD mixing mechanisms.

Note also that the imaginary (CP-violating) part of the K^o-$\overline{K^o}$ mixing seems to come almost exclusively from the SD part. Thus, it is CP violation where both SD physics and heavy flavours become important for the kaon system.

3. CP violation:

An effect of loops and heavy flavours

One of the peculiarities of CP violation is that it is bound to the kaon system. Note that the early evidence for parity violation in the 1950s was also restricted to the kaon system. When CP symmetry was introduced[41] in order to restore the beloved symmetry, the physics community soon had to face a new shock, CP violation[2]. The new phenomenon remained restricted to the K-meson system, but lost something of its mystery after the introduction of the third generation into the SM. The distinguished persistent features of CP violation in the minimal SM are as follows:

- CP violation appears only as a loop effect (i.e. a purely quantum mechanical effect).
- CP-violating amplitudes remain single low-energy amplitudes given by the third generation (i.e. high mass scale).
- The ultimate origin of CP violation resides in the Higgs sector - the least constrained sector of the SM.

Phenomenologically, there are two CP-violating parameters in the game, the one well established[42]

$$\varepsilon = |\varepsilon| e^{i\phi} \quad \begin{cases} |\varepsilon| = (2.3 \pm 0.1) \times 10^{-3} \\ \phi = (45 \pm 2)^{\circ} \end{cases} \tag{22}$$

and the other presently consistent with zero[43,44]

$$\varepsilon'/\varepsilon = \begin{cases} (-4.6 \pm 5.3 \pm 2.4) \times 10^{-3} & \text{(Chicago-Saclay)} \\ (1.7 \pm 8.2) \times 10^{-3} & \text{(BNL-Yale)} \end{cases} \tag{23}$$

They originate from

(i) "indirect CP violation" manifested as $\Delta S=2$ mass matrix effect ($\mathrm{Im}\, M_{12}$)

and/or

(ii) "direct CP violation" in $\Delta S=1$, CP-violating, isospin I=0,2 amplitudes of $K \to 2\pi$ decay,

$$\langle\pi\pi(I)|H_W|K^o\rangle = A_I e^{i\delta_I} \;;\; \omega \equiv \frac{\mathrm{Re}\,A_2}{\mathrm{Re}\,A_o} \simeq \frac{1}{20}\;.$$

According to the phenomenological parametrization,

$$\varepsilon = \frac{e^{i\frac{\pi}{4}}}{2\sqrt{2}}\left[\frac{\mathrm{Im}\,M_{12}}{\mathrm{Re}\,M_{12}} + 2\,\frac{\mathrm{Im}\,A_o}{\mathrm{Re}\,A_o}\right] \tag{24}$$

receives the contributions from both (i) and (ii), while

$$\varepsilon' = \frac{\omega}{\sqrt{2}}\, e^{i(\frac{\pi}{2}+\delta_2-\delta_o)}\left[\frac{\mathrm{Im}\,A_2}{\mathrm{Re}\,A_2} - \frac{\mathrm{Im}\,A_o}{\mathrm{Re}\,A_o}\right] \tag{25}$$

is a pure direct CP-violation effect. In the corresponding expressions[45] obtained in the minimal standard model,

$$\begin{aligned} \varepsilon &\sim B\,\sin\theta_2\,\sin\theta_3\,\sin\delta\;, \\ \varepsilon'/\varepsilon &\sim B'\,\sin\theta_2\,\sin\theta_3\,\sin\delta\;, \end{aligned} \tag{26}$$

we point out the dependence on

(a) $\sin\theta_2\,\sin\theta_3\,\sin\delta$, constrained by measurements of the b-quark lifetime and the $\frac{b\to u}{b\to c}$ branching ratio,

(b) the B parameter, which may determine whether or not the minimal SM can account for ε,

(c) $B' \sim \langle\pi\pi(I=0)|\mathcal{O}_6|K^o\rangle$, the penguin matrix element[46], originally invoked to help in solving the $\Delta I=1/2$ problem.

Adopting "the best values" of Ref. 45, m_t = 45 GeV, B = 0.4, s_3 = 0.025, s_2 = 0.06, δ = 100^o, results in

$$|\varepsilon| \sim 0.6\times\varepsilon^{\mathrm{Expt.}}\;,\quad \frac{\varepsilon'}{\varepsilon} = 12\times10^{-3}\;. \tag{27}$$

Obviously, the B$'$ in (c) should be reduced almost by a factor of 10 in order to avoid the conflict with the measurement[23]. This seems to be possible in view of recent attempts[47,48] to understand the $\Delta I=1/2$ rule in terms of long-distance effects.

Given the uncertainties in both B and B$'$, the ratio ε'/ε still does not represent a serious treat to the minimal SM. Part of ambiguity (especially relevant to the ε parameter) will be eliminated by the more accurate determination[49] of the K-M angles. The precise knowledge of the K-M angles might be important for testing the SM. In this respect there is a recent suggestion[50] that possible small discrepancies from unitarity in the K-M matrix could signal the existence of the fourth generation of quarks (already mentioned[38]). Out of many "beyond the SM", this would then represent the most moderate extension of the SM, just from three to four - or even more? The answer can only be found beyond the SM.

I would like to thank Jan Eeg for many fruitful discussions and Roberto Peccei for warm hospitality at DESY.

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