New physics in Kaons

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1. Why kaons?

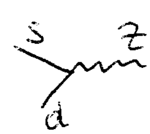
SM: flavor and CP violation governed by

$$V_{CKM} = \begin{array}{c} \\ u \\ c \\ t \\ \\ \end{array} \begin{array}{c} \left(\begin{array}{ccc} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{array} \right) \\ \begin{array}{ccc} d & \quad\quad s & \quad\quad b \end{array} \end{array} + O(\lambda^4)$$

$A \sim 0.82$, $\lambda \sim 0.23$, $\rho \sim 0.14$, $\eta \sim 0.35$

kaon decays: $d \to s$ transitions
↳ governed by $V_{is}^* V_{id}$ $\quad (i = u,c,t)$

CKM unitarity implies $\sum_i V_{is}^* V_{id} = 0$

→ no tree level FCNCs  $= 0$

→ loop effects sensitive to mass of quark (u,c,t) running in the loop ("GIM mechanism")

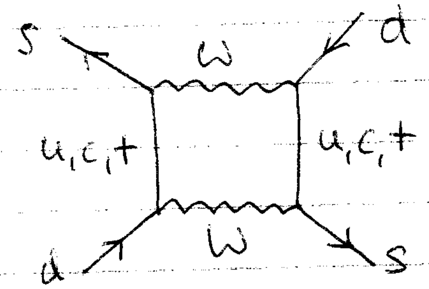
charm quark contribution $\mathcal{O}(\lambda)$, but suppressed by m_c
top quark contribution $\mathcal{O}(\lambda^5)$ + CP violation

$\Rightarrow$ K decays very suppressed in SM
potentially sensitive to very high energy scales

2. $K\bar{K}$ mixing and CP violation

2.1 Brief review of the SM

hep-ph/9806471
chapter 10



time evolution of $K, \bar{K}$ system:

$K^0 = (\bar{s}d)$
$\bar{K}^0 = (\bar{d}s)$

$$i\frac{d\Psi(t)}{dt} = \hat{H}\Psi(t), \quad \Psi(t) = \begin{pmatrix} |K^0(t)\rangle \\ |\bar{K}^0(t)\rangle \end{pmatrix}$$

$$\hat{H} = \hat{M} - i\frac{\hat{\Gamma}}{2} = \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{21} - \frac{i}{2}\Gamma_{21} & M_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix}$$

hermiticity: $M_{21} = M_{12}^*, \quad \Gamma_{21} = \Gamma_{12}^*$
CPT: $M_{11} = M_{22} \equiv M, \quad \Gamma_{11} = \Gamma_{22} \equiv \Gamma$

$\hookrightarrow$ diagonalization of $\hat{H}$ yields mass eigenstates

$$K_{L,S} = \frac{(1+\bar{\varepsilon})K^0 \pm (1-\bar{\varepsilon})\bar{K}^0}{\sqrt{2(1+|\bar{\varepsilon}|^2)}}$$

where $\frac{1-\bar{\varepsilon}}{1+\bar{\varepsilon}} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}$

CP eigenstates:

$$K_{1,2} = \frac{1}{\sqrt{2}}(K^0 \mp \bar{K}^0) \qquad CP\begin{pmatrix}|K_1\rangle \\ |K_2\rangle\end{pmatrix} = \begin{pmatrix}+|K_1\rangle \\ -|K_2\rangle\end{pmatrix}$$

$\Rightarrow$ CP is violated iff $K_{L,S} \neq K_{12}$
(note that phases of $K^0, \bar{K}^0$ are convention dependent)

since $\bar{\varepsilon} \ll 1$ (exp.)

$K_S \cong K_1 + \bar{\varepsilon} K_2$ (mostly CP even)

$K_L \cong K_2 + \bar{\varepsilon} K_1$ (mostly CP odd)

dominating (CP conserving) decay modes

$K_L \to 3\pi$ (via K_2)

$K_S \to 2\pi$ (via K_1)

but they may also decay CP violating

$K_L \to 2\pi$ (via K_1)

$K_S \to 3\pi$ (via K_2)

$\hookrightarrow$ CP violating in mixing

$$\varepsilon_K = \frac{A(K_L \to (\pi\pi)_{I=0})}{A(K_S \to (\pi\pi)_{I=0})}$$

isospin = 0 in order to disentangle from CP violation in decay

$$\Rightarrow \varepsilon_K \cong \frac{\exp(i\pi/4)}{\sqrt{2}\,\Delta M_K} \operatorname{Im} M_{12}$$

SM box diagram
+ QCD effects (RG running, hadronic matrix element)

2.2 New physics contributions

new tree or loop level contributions $\Rightarrow$ effective 4-fermion operators

$$Q_1^{VLL} = (\bar{s}^\alpha \gamma_\mu P_L d^\alpha)(\bar{s}^\beta \gamma^\mu P_L d^\beta) \quad \leftarrow \text{SM}$$
$$Q_1^{VRR} = \quad P_R \quad\quad P_R$$

$$Q_1^{LR} = (\bar{s}^\alpha \gamma_\mu P_L d^\alpha)(\bar{s}^\beta \gamma^\mu P_R d^\beta)$$
$$Q_2^{LR} = (\bar{s}^\alpha P_L d^\alpha)(\bar{s}^\beta P_R d^\beta)$$

$$Q_1^{SLL} = (\bar{s}^\alpha P_L d^\alpha)(\bar{s}^\beta P_L d^\beta)$$
$$Q_2^{SLL} = (\bar{s}^\alpha \sigma_{\mu\nu} P_L d^\alpha)(\bar{s}^\beta \sigma^{\mu\nu} P_L d^\beta)$$

$$Q_1^{SRR}, \; Q_2^{SRR}$$

in many NP models $Q_{1,2}^{LR}$ are generated
- RS: KK gluons
- LR: heavy H^0 exchanges, RH charged currents
- MSSM ...

↳ problematic b/c strongly enhanced by QCD effects
- large anomalous dimension (mostly Q_2^{LR}) similar to quark masses
- matrix element gets "chiral enhancement" $\propto m_K^2 / m_s^2 \gg 1$

3. The $K \to \pi \nu \bar{\nu}$ decays

0801.1833, chapter 3.8

$K^+ \to \pi^+ \nu \bar{\nu}$	$K_L \to \pi^0 \nu \bar{\nu}$
CP conserving $\propto \lvert A(d \to s \nu \bar{\nu}) \rvert^2$	CP violating $\propto [\mathrm{Im}(A(d \to s \nu \bar{\nu}))]^2$
SM: top and charm contributions	top contribution

$K \to \pi \nu \bar{\nu}$ determined by

$$\mathcal{H}_{eff} \propto \Big[\underbrace{V_{cs}^* V_{cd} X_{NL}}_{\text{charm cont.}} + V_{ts}^* V_{td} \underset{\substack{\uparrow \\ \text{SM loop function} \\ \text{(Z penguin + box diagram)}}}{X(x_t)} \Big] (\bar{s}d)_{V-A} (\bar{\nu}\nu)_{V-A}$$

effective operators in (essentially) any NP model
$(\bar{s}d)_{V-A} (\bar{\nu}\nu)_{V-A}$ $\quad$ $(\bar{s}d)_{V+A} (\bar{\nu}\nu)_{V-A}$
(RH neutrinos assumed to be heavy and/or gauge singlets)

relevant matrix elements

$$\langle \pi | (\bar{s}d)_{V-A} | K \rangle = \langle \pi | (\bar{s}d)_{V+A} | K \rangle$$
$$= \langle \pi | (\bar{s}d)_V | K \rangle$$

can be measured in $K^+ \to \pi^0 e^+ \nu$ decay
$\Rightarrow$ theoretically very clean

NP can be parametrised as

$$X(x_t) \to X = |X| e^{i\theta_X}$$

$\hookrightarrow$ measuring both decays can provide $|X|$ and θ_X

some models predict strong correlation between phase of $\Delta S = 2$ (K-$\bar{K}$ mixing) and $\Delta S = 1$ ($K \to \pi \nu \bar{\nu}$)

$\hookrightarrow$ ε_K constraints predicts non-trivial correlation between $K \to \pi \nu \bar{\nu}$ decay modes
measuring a deviation from this correlation would rule out these models

for more details see Intensity Frontier slides and 0904.2528