The contribution of a singlet heavy up-type quark to the mass differences of the neutral K and B–mesons and branching ratios of rare decays $K \to \pi\nu\bar{\nu}$, $B \to \pi\nu\bar{\nu}$ and $B \to K\nu\bar{\nu}$

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M. I. Vysotsky, Phys. Lett. B **644**, 352-354 (2007)
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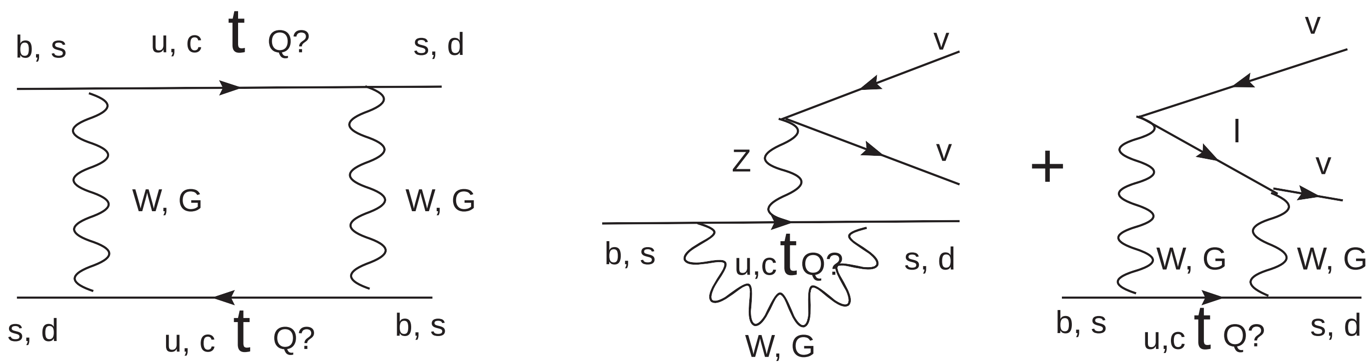
P. N. K. and M. I. Vysotsky, arXiv: 0804.0912[hep-ph].

– Only one new particle found at the LHC - the Standard Model Higgs.

– Is it possible somehow to determine the presence of New Physics by its influence on the loop diagrams? How big can these contributions be?

– New particles have to be sufficiently heavy to avoid direct pair production from gluons, $M \geq 5$ TeV.

– Observables Δm_{B_d}, Δm_{B_s} and ε_K are determined by the box diagrams, decays $K \to \pi\nu\bar{\nu}$, $B \to \pi\nu\bar{\nu}$ and $B \to K\nu\bar{\nu}$ — by penguin + box diagrams:



Here Q is the new heavy up-type quark.

– Diagrams are dominated by the t–quark $\Rightarrow$ Q has to mix with $t \Rightarrow$ its charge is $+\frac{2}{3}$. Mixing with all the up quarks would induce D^0–$\bar{D}^0$ oscillations at tree level and pull their masses to the m_t scale.

– A natural way is to introduce a fourth generation of fermions. Their mass is generated by the Higgs mechanism: $m_{q,\ l} = \lambda_{Yukawa\ \ q,\ l} \cdot \eta/\sqrt{2}$.

– The unitarity leads to:

$$\lambda^2_{Yukawa\ \ q,\ l}/4\pi^2 < 1 \Rightarrow m_{q,\ l} \leq \text{ 1000 GeV}$$

– We need a non-Higgsian mechanism of mass generation $\Rightarrow Q$ is a $SU(2)_L$ – singlet.

Model Lagrangian.

$$\mathcal{L} = \mathcal{L}_{SM} \;+\; \bar{Q}'\,(i\gamma^{\mu}D_{\mu} - M)\,Q' + \Big[\;\; \mu_R \bar{Q}'_L t'_R$$
$$+\;\; \frac{\mu_L}{\eta/\sqrt{2}} H_c^{+} \bar{Q}'_R \cdot \begin{pmatrix} t' \\ b^V \end{pmatrix}_L + c.c.\Big]$$

– Masses: we assume that large m_t arises due to the mixing with the Q,

$$m_t = \frac{\mu_L \mu_R}{M} + O\left(\frac{\mu^4}{M^3}\right), m_Q = M + O\left(\frac{\mu^2}{M}\right)$$

– To express the weak eigenstates through the mass eigenstates we introduce two mixing angles $\theta_{L,R}$:

$$Q'_{L,R} = c_{L,R} \cdot Q_{L,R} + s_{L,R} \cdot t_{L,R},\;\; t'_{L,R} = c_{L,R} \cdot t_{L,R} - s_{L,R} \cdot Q_{L,R}.$$

$s_{L,R} \approx \frac{\mu_{L,R}}{M}$. Only θ_L is relevant to the couplings, $c \equiv c_L,\;\; s \equiv s_L$.

– To maximize the effect $M = 5$ TeV, $\mu_{\rm L} = 500$ GeV, $\mu_R \approx 1,7$ TeV.

The charged and neutral currents.

– The effective CKM matrix $\tilde{V}$ is 4×3, it determines the CC couplings:

$$\tilde{V} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ c \cdot V_{td} & c \cdot V_{ts} & c \cdot V_{tb} \\ s \cdot V_{td} & s \cdot V_{ts} & s \cdot V_{tb} \end{pmatrix}$$

– Although $\tilde{V}^\dagger \cdot \tilde{V} = 1_{3\times 3}$,

$$\tilde{V} \cdot \tilde{V}^\dagger = \begin{pmatrix} 1_{2\times 2} & 0 & 0 \\ 0 & c^2 & cs \\ 0 & cs & s^2 \end{pmatrix}$$

This matrix determines the part of the NC coupling, proportional to $\widehat{T}_3$.
The off-diagonal terms indicate the presence of the $Z_\mu \bar{Q}_L \gamma^\mu t_L$ FCNC.

Δm_{B_d} and Δm_{B_s}

– In the SM the leading contribution is due to the tt–diagram. In the SM the Δm_{B_d} and $\Delta m_{B_s} \propto m_t^2$:

$$\left(\Delta m_{B_{d,s}}\right)_{SM} \;=\; \frac{1}{6\pi^2} G_F^2 B_{B_{d,s}} f_{B_{d,s}}^2 m_{B_{d,s}} \eta_B \cdot \mathcal{R}e\left(\left(V_{tb}{}^* V_{td,s}\right)^2\right) \cdot m_t^2 I\left(\frac{m_t^2}{m_W^2}\right)$$

η_B is responsible for the gluon corrections,
$\langle 0|[\bar{b}\gamma_\mu(1+\gamma^5)q]|B_q\rangle = i f_{B_q} p_{B_q\mu}$,
$\langle \bar{B}_q|[\bar{b}\mathcal{O}_\mu q][\bar{b}\mathcal{O}^\mu q]|B_q\rangle = \frac{8}{3} B_{B_q} \langle \bar{B}_q|[\bar{b}\mathcal{O}_\mu q]|0\rangle\langle 0|[\bar{b}\mathcal{O}^\mu q]|B_q\rangle$

– Taking into the account the new couplings we obtain from the tt, QQ and Qt diagrams respectively:

$$\left(\Delta m_{B_{d,s}}\right)_{NP} = \kappa_{d,s}^{box} \times \left(c^4 m_t^2 I\left(\xi_t\right) + s^4 M^2 I\left(\xi_Q\right) + c^2 s^2 m_t^2 \left(\frac{1}{2}\ln \xi_Q - J(\xi_t)\right)\right)$$

– The effect $\delta_{box} \approx \frac{1}{4} s^4 \frac{M^2}{m_t^2} I\left(\xi_t\right)^{-1} + \frac{1}{2} s^2 \ln \frac{M^2}{m_t^2} I\left(\xi_t\right)^{-1} \propto \frac{\mu_L^4}{m_t^2 M^2} + \frac{\mu_L^2}{M^2} \ln \frac{M^2}{m_t^2} \approx \frac{\mu_L^2}{M^2} \cdot f_{box}(\mu_L, \ln M) \approx 8 \div 9\%$

CP-violation parameter ε_K

– Experimentally Δm_{B_d} and Δm_{B_s} are known with an accuracy of $1 \div 2\%$, $\sqrt{B_B} f_B$ — from lattice calculations — with an accuracy of 10%.
– Observables Δm_{B_d} and Δm_{B_s} do not give us a definite answer.

– $\Delta m_{B_d}/\Delta m_{B_s}$ is measured with an accuracy of $\approx$ 1%, in $\dfrac{\sqrt{B_{B_d}} f_{B_d}}{\sqrt{B_{B_s}} f_{B_s}}$ the error is about $\sim$ 3%. The universal effect δ_{box} cancels out in $\Delta m_{B_d}/\Delta m_{B_s}$.

– ε_K extracted from the experiment:

$$|\tilde{\varepsilon}_{EXP}| = (2.39 \pm 0.05) \times 10^{-3}.$$

– Calculation in the SM:

$$|\tilde{\varepsilon}_{SM}| \equiv \tilde{\varepsilon}^{cc} + \tilde{\varepsilon}^{ct} + \tilde{\varepsilon}^{tt} = (-0.06 + 0.92 + 1.99) \times 10^{-3} = (2.83 \pm 0.50) \times 10^{-3}.$$

Errors come from the B_K — $\approx 3.5\%$ (we use the RBC/UKQCD Summer 2007 result: $B_K = 0.770 \pm 0.027$), from $\mathcal{I}m(V_{ij})$ — $15 \div 17\%$.
– The effect of New Physics:

$$|\tilde{\varepsilon}_{NP}| \equiv \tilde{\varepsilon}^{cc} + \tilde{\varepsilon}^{ct} + \tilde{\varepsilon}^{tt} \times (1 + \delta_{box}) = (3,01 \pm 0,53) \times 10^{-3}, \sigma_{\tilde{\varepsilon}_{NP}} = 17,5\%.$$

Experimental constraints on the Q mass

– Universal effect $\delta_{box} \approx \frac{\mu_L^2}{M^2} \cdot f_{box}(\mu_L, \ln M)$, $f_{box} \approx 10$, the maximum value δ_{box} corresponds to

$$\Big| |\tilde{\varepsilon}_{NP}(\delta_{box})| - |\tilde{\varepsilon}_{EXP}| \Big| = 2\sigma_{\tilde{\varepsilon}_{NP}} \text{ or } 3\sigma_{\tilde{\varepsilon}_{NP}}.$$

– Experimental constraint: $M^2 \geq \ \mu_L^2 \cdot f_{box}(\mu_L, \ln M) \cdot (\delta_{box})^{-1} \Rightarrow$

$$M \geq \ 2.5 \text{ TeV at } 2\sigma, \ \text{M} \geq \ 1.5 \text{ TeV at } 3\sigma.$$

The rare decays $K \to \pi\nu\bar{\nu}$, $B \to \pi\nu\bar{\nu}$ and $B \to K\nu\bar{\nu}$

– Electroweak penguins are dominated by the t–quark (only for $K^+ \to \pi^+\nu\bar{\nu}$ one has to take the c–quark into account).

– They are "theoretically clean" — the CKM matrix elements are going to be measured with a $\approx 1\%$ accuracy.

– The hadronic matrix elements $\langle \pi^{0+} | \bar{b}(\bar{s})_L \gamma_\mu d_L | B(K)^{0+} \rangle$ are equal to the matrix elements $\langle \pi^{-0} | \bar{b}(\bar{s})_L \gamma_\mu u_L | B(K)^{0+} \rangle$ respectively with the accuracy of the isospin $SU(2)$ symmetry violation.

– These m.e. can be extracted from the $B(K)^{0+} \to \pi^{-0} \nu e^+$ decay widths.

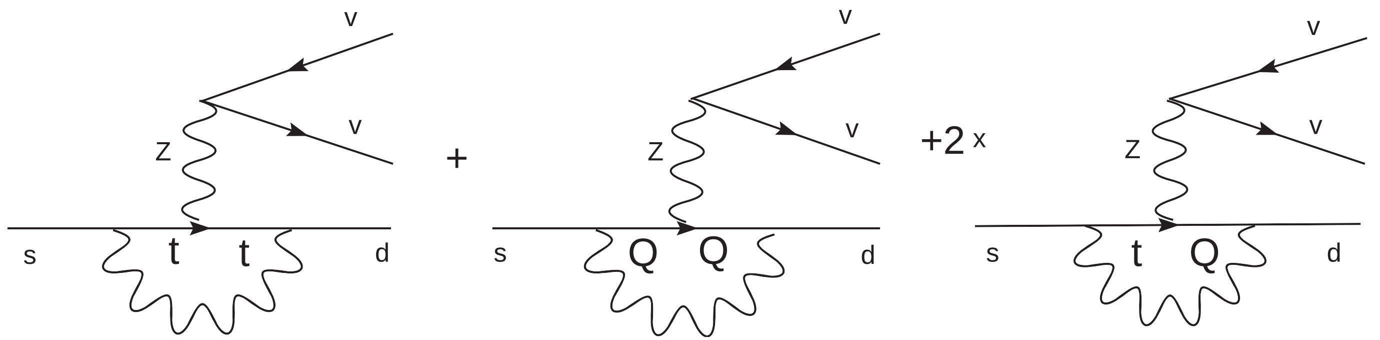
– For the $B \to K\nu\bar{\nu}$ width the corresponding accuracy is worse — of order of the $SU(3)$ symmetry violation $\approx 20\%$.

The Lagrangian of the $K \to \pi\nu\bar{\nu}$ decays

– In the SM the effective Lagrangian $\mathcal{L}_{eff}^{SM}(s \to d\nu\bar{\nu}) = (\mathcal{L}_t)_{SM} + \mathcal{L}_c$,

$$(\mathcal{L}_t)_{SM} = \frac{G_F^2 m_W^2}{4\pi^2}\ \bar{d}_L \gamma^\mu s_L \sum_{l=e,\mu,\tau} \bar{\nu}_L^{(l)} \gamma_\mu \nu_L^{(l)} \cdot V_{td}^* V_{ts} \xi_t\ F(\xi_t)\ \eta_X$$

– When the modification of the couplings, the diagrams with the $Q-$ quark and the FCNC are taken into account:



$$(\mathcal{L}_t)_{NP} = \kappa^p \times \left(c^4 m_t^2 F(\xi_t) + s^4 M^2 + 2c^2 s^2 m_t^2 \left(\frac{\xi_t - 1}{\xi_t} \ln \frac{M^2}{m_t^2} - G(\xi_t) \right) \right)$$

The effect of the New Physics on the branching ratios

– The effect $\delta_p \approx s^4 \frac{M^2}{m_t^2} F(\xi_t)^{-1} + 2c^2 s^2 \ln \frac{M^2}{m_t^2} F(\xi_t)^{-1} - \delta_{charm} \propto \frac{\mu_L^4}{m_t^2 M^2} + \frac{\mu_L^2}{M^2} \ln \frac{M^2}{m_t^2} - \delta_{charm} \approx \frac{\mu_L^2}{M^2} \cdot f_p(\mu_L, \ln M) - \delta_{charm}, \;\; f_p \approx 5.0$

– Contributions of each of the up quarks are $\propto m_i^2 V_{ib(s)} V^*_{is(d)}$.

– $K_L \to \pi^0 \nu\bar{\nu}$ proceeds via the CPV mechanism $\Rightarrow \mathcal{I}m(V_{is}V^*_{id})$, charm contribution is suppressed as m_c^2/m_t^2.

– $B \to K(\pi)\nu\bar{\nu}$ contain $V_{ib}V^*_{is(d)}$, charm contribution is again suppressed as m_c^2/m_t^2.

– Branching ratios: $\delta_{\mathrm{Br}} \equiv \frac{Br(B(K)\to K(\pi)\nu\bar{\nu})_{NP} - Br(B(K)\to K(\pi)\nu\bar{\nu})_{SM}}{Br(B(K)\to K(\pi)\nu\bar{\nu})_{SM}}$

$$\delta_{\mathrm{Br}} = 2\delta_p \approx \begin{cases} 8\% & K_L \to \pi^0\nu\bar{\nu}, B \to \pi\nu\bar{\nu}, B \to K\nu\bar{\nu} \\ 6\% & K^+ \to \pi^+\nu\bar{\nu} \end{cases}$$

Present-day experimental results

– PDG (2006):

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (1.5^{+1.3}_{-0.9}) \times 10^{-10},$$
$$Br(K_L \to \pi^0 \nu\bar{\nu}) < 5.9 \times 10^{-7},$$
$$Br(B_u \to \pi^+ \nu\bar{\nu}) < 1.0 \times 10^{-4},$$
$$Br(B_u \to K^+ \nu\bar{\nu}) < 5.2 \times 10^{-5}.$$

– Heavy Flavor Averaging group (August 2007) :

$$Br(B_u \to K^+ \nu\bar{\nu}) < 1.4 \times 10^{-5}.$$

– J. K. Ahn *et al.*, e-Print: arXiv:0712.4164 (December 2007):

$$Br(K_L \to \pi^0 \nu\bar{\nu}) < 6.7 \times 10^{-8}.$$

– The current state of the experiment does not allow us to make any conclusions concerning the existence of the New Physics.

The future plans

- the measurement of $Br(K^+ \to \pi^+\nu\bar{\nu})$ at the CERN SPS NA62 experiment with $\approx$ 10% accuracy, the data taking is planned for 2009–2010;

- the measurement of $Br(B_u \to K^+\nu\bar{\nu})$ at the Super B Factory experiment with the accuracy $\leq$ 20% by 2014–2015;

- the measurement of $Br(K^+ \to \pi^+\nu\bar{\nu})$ at the J-PARC experiment with the accuracy $\leq$ 20% after 2012–2013;

- the measurement of $Br(K_L \to \pi^0\nu\bar{\nu})$ at the J-PARC experiment with the accuracy $\leq$ 10% after 2010.

Conclusions.

– The mass differences Δm_{B_d}, Δm_{B_s}, the CP–violation parameter ε_K and the widths of the $B(K) \to K(\pi)\nu\bar{\nu}$ decays obtain in our model up to 10% corrections.

– Hadronic uncertainties in $\sqrt{B_B} f_B$ do not allow us to make any decisive statement based on the $\Delta m_{B_{d,s}}$.

– These uncertainties are absent in the case of the $B(K) \to K(\pi)\nu\bar{\nu}$ branching ratios, and the situation with the CKM matrix elements is bound to improve in the near future.

– Provided that they have the proper accuracy the future experiments at J-PARC, Super B and SPS will allow to discover New Physics or to establish the lower bounds on the mass of the heavy quark Q.