The CKM unitarity problem: A trace of new physics at the TeV scale?

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Contents

Based on

B. Belfatto, R. Beradze and Z. Berezhiani, *"The CKM unitarity problem: A trace of new physics at the TeV scale?,"* arXiv:1906.02714 [hep-ph]; Eur. Phys. J. C (in press)

B. Belfatto and Z. B., *"How light the lepton flavor changing gauge bosons can be,"* Eur. Phys. J. C **79**, 202 (2019); arXiv:1812.05414 [hep-ph]

Z. B., *"Neutron lifetime puzzle and neutron–mirror neutron oscillation,"* Eur. Phys. J. C **79**, 484 (2019) arXiv:1807.07906 [hep-ph]

Standard Model $SU(3) \times SU(2) \times U(1)$

Three fermion families:
LH doublets $q_{Li} = (u_L, d_L)$, $\ell_{Li} = (\nu_L, e_L)$ & RH singlets u_R, d_R, e_R.

Weak eigenstates are not mass eigenstates

$$\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} \begin{pmatrix} \overline{u} & \overline{c} & \overline{t} \end{pmatrix}_L \gamma^\mu W^+_\mu \mathbf{V}_{\rm CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L$$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$ is unitary

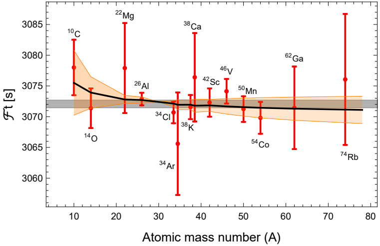
First row unitarity $\quad |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

... $|V_{ub}|^2 \approx 1.6 \times 10^{-5}$ $\quad$ Cabibbo universality: $\cos^2\theta_C + \sin^2\theta_C = 1$

$|V_{ud}|$ from superallowed $0^+ - 0^+$ decays

(pure Fermi transitions – g_A independent)

Corrected *ft*-values: $\mathcal{F}t = ft(1 + \delta'_R + \delta_{NS} - \delta_C)$ – transition independent



$\overline{\mathcal{F}t} = 3072.07(72)$ s
Hardy & Towner, 2015

$$G_F^2 |V_{ud}|^2 = \frac{K}{2\mathcal{F}t\,(1+\Delta_R)}$$

$$K = \frac{2\pi^3 \ln 2}{m_e^5} = 8120.2776(9)\,\frac{10^{-10}\,\mathrm{s}}{\mathrm{GeV}^4} \qquad G_F = G_\mu = 1.1663787(6)\,\frac{10^{-5}}{\mathrm{GeV}^2}$$

Short-distance (transition independent) electroweak corrections

Marciano Sirlin 2006: $\Delta_R = 2.361(38)\ \%$

$$|V_{ud}| = 0.97420(10)_{\mathcal{F}t}(18)_{\Delta_R} = 0.97420(21)$$

Seng et al. 2018: $\Delta_R = 2.467(22)\ \%$

$$|V_{ud}| = 0.97370(10)_{\mathcal{F}t}(10)_{\Delta_R} = 0.97370(14)$$

$|V_{us}|$ and $|V_{us}/V_{ud}|$ from Kaons

Semileptonic $K \to p\ell\nu$ decays: $f_+(0)|V_{us}| = 0.21654(41)$

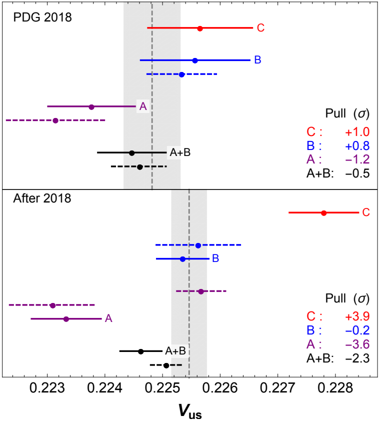
The ratio of leptonic K/π decays: $\left|\frac{V_{us}}{V_{ud}}\right| \frac{f_{K^\pm}}{f_{\pi^\pm}} = 0.27599(38)$

vector formfactor $f_+(0)$ and decay constants f_K/f_π from Lattice QCD ($2+1$ and $2+1+1$ simulations)

PDG 2018 refers to FLAG 2017 results for Lattice QCD and adopts
$|V_{us}| = 0.2238(8)$
$|V_{us}/V_{ud}| = 0.2315(10)$
$|V_{us}| = 0.97420(21)$ taking Marciano-Sirlin '06 Δ_R

Seng et al 2018 redetermination of Δ_R:
$|V_{ud}| = 0.97370(10)_{\mathcal{F}t}(10)_{\Delta_R} = 0.97370(14)$
New determinations of the ratio for kaon and pion decay constant $f_{K^\pm}/f_{\pi^\pm}$ (FLAG 2019) and of the form factor relevant for semileptonic decay $f_+(0)$ (Fermilab Lattice and MILC);
$\mathbf{|V_{us}| = 0.22333(60)}$, $\mathbf{\left|\frac{V_{us}}{V_{ud}}\right| = 0.23130(50)}$

$|V_{us}|$ determinations assuming CKM unitarity:
Old (PDG 2018) and New (after 2018)



$$|V_{ud}|^2 + |V_{us}|^2 = 1 - |V_{ub}|^2 = 1$$

$$\cos^2\theta_C + \sin^2\theta_C = 1$$

$$\dots\ |V_{ub}|^2 \approx 1.6\times10^{-5}$$

A: $|V_{us}|$ from $K \to \pi\ell\nu\ (f_+)$

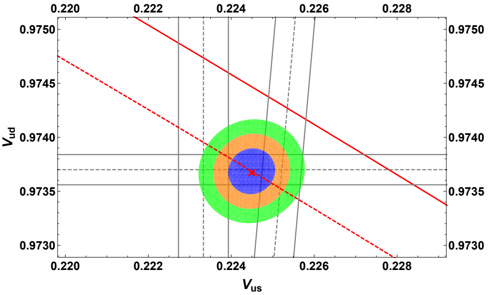
B: $|V_{us}|$ from $|\frac{V_{us}}{V_{ud}}|$ – K/π ratio

C: $|V_{us}| = \sqrt{1-|V_{ud}|^2}$ from 0^+–0^+

PDG 2018 based on:
A & B: FLAG 17
C: Δ_R Marciano-Sirlin '06

After 2018 based on:
A & B: FLAG 19 + MILC 19 + DiCarlo 19
C: Δ_R Seng et al '18

Solution 1: extra quarks (b', t'): CKM 4 vs. CKM 3



CKM

$$|V_{ud}|^2+|V_{us}|^2 = 1-|V_{ub}|^2$$

$$|V_{ud}|^2+|V_{us}|^2 = 1-|V_{ub}|^2-|V_{ub'}|^2 \quad \ldots \; |V_{ub'}| \approx 0.04 \; (\gg |V_{ub}| \approx 0.004)$$

Modifiying 3 family CKM to 4 families?

$$\tilde{V}_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{pmatrix}$$

How to introduce 4-th family?

SM: 3 sequential chiral families:

LH isodoublets $Q_{Li} = \begin{pmatrix} u_L \\ d_L \end{pmatrix}_i$ and RH isosinglets $\begin{matrix} u_{Ri} \\ d_{Ri} \end{matrix}$ $(i = 1, 2, 3)$

– mass eigenstates are u, c, t and d, s, b.

4-th sequential chiral family $Q_{L4} = \begin{pmatrix} t'_L \\ b'_L \end{pmatrix}$ $\begin{matrix} u_{R4} = t'_R \\ d_{R4} = b'_R \end{matrix}$ – excluded !

(by the SM precision (S, T, U), LHC limits, Higgs 2γ decay)

A vector-like isodoublets $Q_{L4} = \begin{pmatrix} t'_L \\ b'_L \end{pmatrix}$ $Q_{R4} = \begin{pmatrix} t'_R \\ b'_R \end{pmatrix}$ .... useless !

(cannot give large enough $|V_{ub'}| = 0.04$)

Vector-like isosinglets $\begin{matrix} t'_L \\ b'_L \end{matrix}$ and $\begin{matrix} t'_R \\ b'_R \end{matrix}$ – can work

Mass terms $M\overline{b'_L}b'_R$ and/or $M\overline{t'_L}t'_R$ $M > 1$ TeV or so ...

How it works?

- Forth vector-like quark $d_{4L,R}$ whose left and right components are both $SU(2)$ singlets involved in quark mixing:

$$\ldots + h_i \phi \overline{q_{Li}} d_{4R} + M \overline{d_{4L}} b_{4R} + h.c.$$

- $$\overline{d_{Li}} \mathbf{m}^{(d)}_{ij} d_{Rj} = (\overline{d_{1L}}, \overline{d_{2L}}, \overline{d_{3L}}, \overline{d_{4L}}) \left(\begin{array}{ccc|c} & & & h_d v \\ & \mathbf{m}^{(d)}_{3\times 3} & & h_s v \\ & & & h_b v \\ \hline 0 & 0 & 0 & M \end{array} \right) \begin{pmatrix} d_1 \\ d_2 \\ d_3 \\ d_4 \end{pmatrix}_R$$

- $$\tilde{V}_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & \boxed{V_{ub'}} \\ V_{cd} & V_{cs} & V_{cb} & \boxed{V_{cb'}} \\ V_{td} & V_{ts} & V_{tb} & \boxed{V_{tb'}} \end{pmatrix} = V_L^{(u)\dagger} \tilde{V}_L^{(d)} \; ;$$

- $\tilde{V}_L^{(d)}$ is the 3×4 submatrix of $V_L^{(d)}$, $V_L^{(d)\dagger} \mathbf{m}^{(d)} V_R^{(d)} = \mathbf{m}^{(d)}_{\rm diag}$.
- Since $V_{ub'} \simeq h_d v_w / M$, assuming $|V_{ub'}| > 0.03$ (95% C.L.) and $h_d < 1$, then $M < 6$ TeV.

Flavor Changing Neutral Currents (FCNC)

- The forth quark has tree level flavor-changing couplings with the Higgs boson and with Z-boson. So for down quarks:

$$\mathcal{L}_{\rm nc} = -\frac{1}{2}\frac{g}{\cos\theta_W} Z_\mu \left(\overline{d_L} \quad \overline{s_L} \quad \overline{b_L} \quad \overline{b'_L} \right) \gamma^\mu \tilde{V}_L^{(d)\dagger} \tilde{V}_L^{(d)} \begin{pmatrix} d \\ s \\ b \\ b' \end{pmatrix} + \text{diagonal}$$

Elements	Constraint	Process	$\lvert V_{ub'}\rvert = 0.04$
$\lvert V_{ub'}V^*_{cb'}\rvert$	$< 5\cdot 10^{-5}$	$K^+ \to \pi^+\nu\bar\nu$	$\lvert V_{cb'}\rvert < 0.0013$
$\lvert {\rm Im} V_{ub'}V^*_{cb'}\rvert$	$< 8\cdot 10^{-6}$	$K_S \to \mu^+\mu^-$	
$\lvert {\rm Re} V_{ub'}V^*_{cb'}\rvert$	$< 1.5\cdot 10^{-5}$	$K_L \to \mu^+\mu^-$	
$\lvert V_{ub'}V^*_{tb'}\rvert$	$< 4\cdot 10^{-4}$	$B^+ \to \pi^+\ell^+\ell^-$	$\lvert V_{tb'}\rvert < 0.01$
$\lvert {\rm Re} V_{ub'}V^*_{tb'}\rvert$	< 0.0001	$B \to \mu^+\mu^-$	
$\lvert V_{cb'}V^*_{tb'}\rvert$	< 0.002	$B^0 \to X_s\mu^+\mu^-$	
$\lvert {\rm Re} V_{cb'}V^*_{tb'}\rvert$	< 0.0006	$B^0_s \to \mu^+\mu^-$	

t' vs. b' – again FCNC)

- Forth vector-like up-type quark $u_{4L,R}$ whose left and right compone are both $SU(2)$ singlets involved in quark mixing:

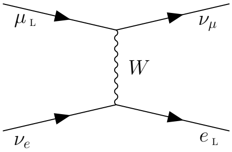
$$\ldots + h_i \tilde{\phi} \overline{q_{Li}} u_{4R} + M_u \overline{u_{4L}} u_{4R} + h.c.$$

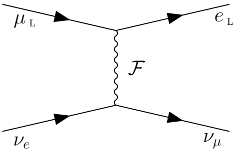
- $$\tilde{V}_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \\ V_{t'd} & V_{t's} & V_{t'b} \end{pmatrix} = \tilde{V}_L^{(u)\dagger} V_L^{(d)} \; ;$$

- $\tilde{V}_L^{(u)}$ is the 3×4 submatrix of $V_L^{(u)}$.

Elements	Constraint	Process	$\lvert V_{t'd}\rvert = 0.04$
$\lvert V^*_{t'd} V_{t's}\rvert$	0.00012	D^0 mixing	$\lvert V_{t's}\rvert < 0.003$
$\lvert \mathrm{Re} V^*_{t'd} V_{t's}\rvert$	0.003	$D^0 \to \mu^+\mu^-$	
$\lvert V^*_{t'b} V_{t'd}\rvert$	0.002	B^0 mixing	$\lvert V_{t'b}\rvert < 0.05$
$\lvert V^*_{t'b} V_{t's}\rvert$	0.01	B^0_s mixing	

Solution 2: extra (leptonic) interactions: $G_F \neq G_\mu$





$G_F/\sqrt{2} = g^2/8M_W^2 = 1/4v_{\rm w}^2$

$v_{\rm w} = 174$ GeV – EW scale

$G_{\mathcal{F}}/\sqrt{2} = g_H^2/8M_{\mathcal{F}}^2 = 1/4v_{\mathcal{F}}^2$

$v_{\mathcal{F}} \sim$ few TeV – flavor scale

After Fierz transformation, the sum of diagrams gives the operator:

$$-\frac{4G_\mu}{\sqrt{2}}(\overline{\nu_\mu}\gamma^\alpha\mu_L)(\overline{e_L}\gamma_\alpha\nu_e)$$

$$G_\mu = G_F + G_{\mathcal{F}} = G_F(1+\delta_\mu) \qquad \delta_\mu = G_{\mathcal{F}}/G_F = (v_{\rm w}/v_{\mathcal{F}})^2 > 0$$

New interactions have positive interference with SM, i.e. $G_\mu > G_F$

$$|V_{ud}|^2 = \frac{K}{2G_F^2\mathcal{F}t\,(1+\Delta_R)} = \frac{K\,(1+\delta_\mu)^2}{2G_\mu^2\mathcal{F}t\,(1+\Delta_R)}$$

$G_\mu = G_F\,(1+\delta_\mu)$

$$|V_{ud}|^{\rm new} \;\to\; |V_{ud}|^{\rm old} \times (1+\delta_\mu)$$

and respectively $|V_{us}| = \sqrt{1-|V_{ud}|^2-|V_{ub}|^2}$ is shifted down

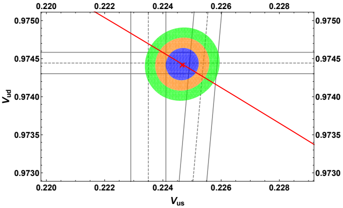
... and $|V_{us}|$ determined from $K\to\pi\ell\nu$ decays moves up:

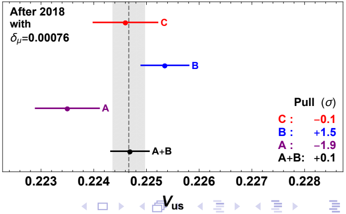
$$|V_{us}|^{\rm new} \;\to\; |V_{us}|^{\rm old} \times (1+\delta_\mu)$$

while determination of $|V_{us}/V_{ud}|$ from ratio of K^+ and π^+ leptonic decays remains invariant:

$$|V_{us}/V_{ud}|^{\rm new} \;=\; |V_{us}/V_{ud}|^{\rm old}$$

Chosing e.g. $\delta_\mu = 7.5\times 10^{-4}$, which corresponds to $v_{\mathcal F} = 6.3$ TeV the situation of CKM unitarity changes to





Standard Model: *the Good, the Bad, the Ugly ...*

- Weak eigenstates are not mass eigenstates;
- fermion mass matrices

$$m_{ij}^{(f)} = Y_{ij}^{f} v_{\rm EW}$$

$v_{\rm EW} = 174$ GeV, can be diagonalized $V_L^{(f)\dagger} m^{(f)} V_R^{(f)} = m_{\rm diag}^{(f)}$;

- all masses proportional to Higgs VEV;
- fermion mixing in charged currents is

$$V_{\rm CKM} = V_L^{(u)\dagger} V_L^{(d)} \qquad U_{\rm PMNS} = V_L^{(\nu)\dagger} V_L^{(e)};$$

- Yukawa couplings, and photon/Z couplings ($V^\dagger V = 1$), are diagonal in mass basis: **no flavour changing neutral currents at tree level**;
- all flavour changing and CP-violation is originated from loop diagrams;
- no mixing in the right particles sector (unless right W bosons exist).

Standard Model: *the Good, the Bad, the Ugly ...*

Something not explained in the SM:

- Replication of fermion **families**;
- inter-family **mass hierarchy** (**Yukawa hierarchy**);
- weak **mixing pattern**: small angles for quarks, large angles for neutrinos;
- neutrino masses: very small (seesaw?), mass hierarchy yet unknown.

Hierarchy between quarks and CKM angles parametrized by $\epsilon \sim 1/20$:

$$m_d : m_s : m_b \sim \epsilon^2 : \epsilon : 1 \qquad m_u : m_c : m_t \sim \epsilon^4 : \epsilon^2 : 1$$

$$\sin\theta^q_{12} \sim \sqrt{\epsilon} \sim 4\epsilon; \quad \sin\theta^q_{23} \sim \epsilon; \quad \sin\theta^q_{13} \sim \epsilon^2$$

Hierarchy between charged leptons parametrized by same $\epsilon \sim 1/20$:

$$m_e : m_\mu : m_\tau \sim k^{-1}\epsilon^2 : k\epsilon : k$$

$k \simeq 3$ (factor $O(1)$).

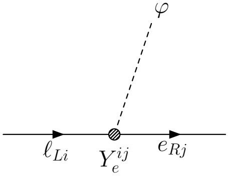
Technically natural: SM tolerates Yukawa hierarchy but cannot explain it.

Family symmetries

In the SM fermion masses emerge from the Yukawa couplings:

$$Y_u^{ij}\,\tilde{\varphi}\,\overline{Q_{Li}}\,u_{Rj} + Y_d^{ij}\,\varphi\,\overline{Q_{Li}}\,d_{Rj} + Y_e^{ij}\,\varphi\,\overline{\ell_{Li}}\,e_{Rj} + \mathrm{h.c.}$$

φ is the the Higgs doublet and $\tilde{\varphi} = i\tau_2\varphi^*$; $i, j = 1, 2, 3$ family indexes



Fermion masses cannot emerge without EW symmetry breaking

In the limit of vanishing Yukawa couplings $Y_{u,d,e} \to 0$ the SM acquires a maximal global symmetry $U(3)_Q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$

One can consider $SU(3)$ parts as gauge symmetries

Family gauge symmetry $SU(3)_\ell \times SU(3)_R$

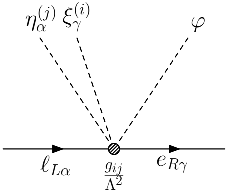
Let us discuss the leptonic sector and gauge family symmetry $SU(3)_\ell \times SU(3)_e$

$$\ell_{L\alpha} = \begin{pmatrix} \nu_\alpha \\ e_\alpha \end{pmatrix}_L \sim (\mathbf{3}_\ell, 1), \quad e_{R\gamma} \sim (1, \mathbf{3}_e)$$

$\alpha = 1,2,3$ and $\gamma = 1,2,3$ are indexes of $SU(3)_\ell$ and $SU(3)_e$

Fermion masses cannot emerge only by Higgs VEV $\langle\phi\rangle \neq 0$: flavor symmetry must be broken also.

Flavons $\eta_\alpha^{1,2,3}$ and $\xi_\gamma^{1,2,3}$ (3 $SU(3)_\ell$ triplets & 3 $SU(3)_e$ triplets)



Their VEVs break $SU(3)_\ell$ and 3 triplets of $SU(3)_e$ and induce fermion masses via effective operators: $\frac{g_{ij}}{\Lambda^2}\,\overline{\xi_i^\gamma}\eta_{j\alpha}\phi\,\overline{\ell_{L\alpha}}e_{R\gamma} + \text{h.c.}$

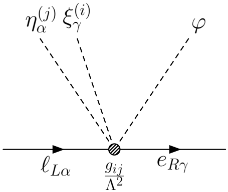
Λ is the large cutoff scale and $g_{ij} \sim 1$

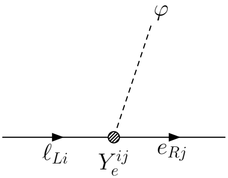
Breaking $SU(3)_\ell \times SU(3)_R$

Flavon basis can be chosen so that $\langle \eta_{i\alpha} \rangle = w_i \delta_{i\alpha}$ and $\langle \xi_{i\gamma} \rangle = v_i \delta_{i\gamma}$

$$\langle \eta_1 \rangle = \begin{pmatrix} u_1 \\ 0 \\ 0 \end{pmatrix} \quad \langle \eta_2 \rangle = \begin{pmatrix} 0 \\ u_2 \\ 0 \end{pmatrix} \quad \langle \eta_3 \rangle = \begin{pmatrix} 0 \\ 0 \\ u_3 \end{pmatrix}; \qquad u_3 \sim u_2 \sim u_1$$

$$\langle \xi_1 \rangle = \begin{pmatrix} v_1 \\ 0 \\ 0 \end{pmatrix} \quad \langle \xi_2 \rangle = \begin{pmatrix} 0 \\ v_2 \\ 0 \end{pmatrix} \quad \langle \xi_3 \rangle = \begin{pmatrix} 0 \\ 0 \\ v_3 \end{pmatrix}; \qquad v_3 \gg v_2 \gg v_1$$

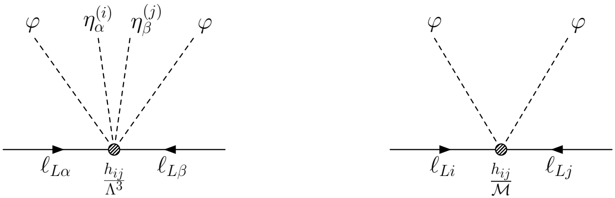




Effective operators reduce to SM Yukawas: $Y_e^{ij} = g_{ij} u_i v_j / \Lambda^2$

Charged lepton and neutrino masses and mixing

Analogously for neutrinos



Because of hierarchy pattern $v_1 : v_2 : v_3 \simeq \varepsilon^2 : \varepsilon : 1$,
the charged lepton mass hierarchy $m_e : m_\mu : m_\tau \simeq \tilde{\varepsilon}\varepsilon : \varepsilon : 1$:

$$M_e \simeq \begin{pmatrix} g_{11}\varepsilon\tilde{\varepsilon} & g_{12}\varepsilon & g_{13} \\ g_{21}\varepsilon\tilde{\varepsilon} & g_{22}\varepsilon & g_{23} \\ g_{31}\varepsilon\tilde{\varepsilon} & g_{32}\varepsilon & g_{33} \end{pmatrix} \times (u_3 v_3 v_{\rm w}/\Lambda^2)$$

But because of democratic pattern $u_1 : u_2 : u_3 \simeq 1 : 1 : 1$ the neutrino (Majorana) mass matrix is democratic – large neutrino mixing angles!

$$M_\nu \simeq \begin{pmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{pmatrix} \times (u_3^2 v_{\rm w}^2/\Lambda^3)$$

FCNC: $SU(2)_e$ gauge bosons ...

In $\mathbf{SU(2)_e}$ gauge symmetry limit ($v_3 \gg v_2$):

- $SU(2)_e$ gauge bosons have equal masses;
- there are no FCNC thanks to **CUSTODIAL SYMMETRY**, no matter if two families are mixed:

$$\mathcal{L}_{eff} = -\frac{1}{4v_2^2}(\overline{\mathbf{e}_\mathrm{R}}\tau^{a*}\gamma^\mu \mathbf{e}_\mathrm{R})(\overline{\mathbf{e}_\mathrm{R}}\tau^{a*}\gamma_\mu \mathbf{e}_\mathrm{R})$$

$$= -\frac{1}{4v_2^2}(\overline{e_{\mathrm{R}1}}\gamma_\mu e^1 + \overline{e_{\mathrm{R}2}}\gamma_\mu e^2_\mathrm{R})^2 =$$

$$= -\frac{1}{4v_2^2}\left(\begin{pmatrix} \bar{e} & \bar{\mu} & \bar{\tau} \end{pmatrix}\gamma^\mu V^{(e)\dagger} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix} V^{(e)} \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}\right)^2_R$$

NO MIXING WITH 3rd FAMILY $\longrightarrow$ NO FCNC.

- Then constraints on masses are proportional to violation of custodial symmetry (corrections of order $\epsilon = v_2/v_3$):

$$\mathcal{L}_{eff} = -\frac{1}{4v_2^2}(J_{(2)})^2 - \frac{1}{4v_3^2}(J_3 + \sqrt{3}J_8)^2 - \frac{1}{v_3^2}\sum_{a=4}^{7}(J_a)^2$$

FCNC: $SU(2)_e$ gauge bosons ...

Compositeness limits:

$$\mathcal{L}_C = \pm \frac{g^2}{(1+\delta_{ef})\Lambda^2_{RR}} \bar{e_R}\gamma_\mu e_R \bar{f}_R \gamma^\mu f_R$$

$$\frac{g^2}{4\pi} = 1$$

$$\Lambda^-_{RR}(eeee) > 10.2\,\text{TeV}$$
$$\Lambda^-_{RR}(ee\mu\mu) > 9.1\,\text{TeV}$$
$$\Lambda^-_{RR}(ee\tau\tau) > 5.5\,\text{TeV}$$

$$\boxed{v_2 > 2\,\text{TeV}} \longrightarrow v_3 > 40\text{TeV}$$

LFV mode	Exp. $\Gamma_i/\Gamma_\mu(\Gamma_\tau)$	Main contribution to $\frac{\Gamma_i}{\Gamma_{\mu/\tau}}$	Predicted value of $\frac{\Gamma_i}{\Gamma_{\mu/\tau}}$
$\mu \to eee$	$< 1.0 \cdot 10^{-12}$	$\frac{1}{8}\left(\frac{v_{\rm EW}}{v_2}\right)^4 \left\lvert V^*_{3e}V_{3\mu} + V^*_{2e}V_{2\mu}\epsilon^2\right\rvert^2$	$\leq 1.1 \cdot 10^{-13}\left(\frac{2\,\text{TeV}}{v_2}\right)^4 \epsilon^4_{20}\tilde{\epsilon}^2_{20}$
$\tau^- \to \mu^- e^+ e^-$	$< 1.8 \cdot 10^{-8}$	$\frac{1}{4}\left(\frac{v_{\rm EW}}{v_2}\right)^4 \left\lvert V^*_{3\mu}V_{3\tau}\right\rvert^2 \frac{\Gamma_{\rm w}}{\Gamma_\tau}$	$= 6.2 \cdot 10^{-9}\left(\frac{2\,\text{TeV}}{v_2}\right)^4 \epsilon^2_{20}$
$\tau \to \mu\mu\mu$	$< 2.1 \cdot 10^{-8}$	$\frac{1}{8}\left(\frac{v_{\rm EW}}{v_2}\right)^4 \left\lvert V^*_{3\mu}V_{3\tau}\right\rvert^2 \frac{\Gamma_{\rm w}}{\Gamma_\tau}$	$= 3.1 \cdot 10^{-9}\left(\frac{2\,\text{TeV}}{v_2}\right)^4 \epsilon^2_{20}$
$\mu \to e\gamma$	$< 4.2 \cdot 10^{-13}$	$\frac{3\alpha}{2\pi}\left(\frac{v_{\rm EW}}{v_2}\right)^4 \left\lvert V^*_{3e}V_{3\mu}\right\rvert^2$	$= 3.1 \cdot 10^{-15}\left(\frac{2\,\text{TeV}}{v_2}\right)^4 \epsilon^4_{20}\tilde{\epsilon}^2_{20}$
$\tau \to \mu\gamma$	$< 4.4 \cdot 10^{-8}$	$\frac{3\alpha}{2\pi}\left(\frac{v_{\rm EW}}{v_2}\right)^4 \left\lvert V^*_{3\mu}V_{3\tau}\right\rvert^2 \frac{\Gamma_{\rm w}}{\Gamma_\tau}$	$= 8.7 \cdot 10^{-11}\left(\frac{2\,\text{TeV}}{v_2}\right)^4 \epsilon^2_{20}$

FCNC: $SU(2)_\ell$ gauge bosons ...

$SU(3)_l \times SU(3)_e$

$$\frac{1}{2}\begin{pmatrix} \theta_3+\frac{1}{\sqrt{3}}\theta_8 & \theta_1-i\theta_2 & \theta_4-i\theta_5 \\ \theta_1+i\theta_2 & -\theta_3+\frac{1}{\sqrt{3}}\theta_8 & \theta_6-i\theta_7 \\ \theta_4+i\theta_5 & \theta_6+i\theta_7 & -\frac{2}{\sqrt{3}}\theta_8 \end{pmatrix}^{(\ell}$$

$$M^2_{4,5}=\frac{g^2}{2}(u_3^2+u_1^2) \qquad M^2_{6,7}=\frac{g^2}{2}(u_3^2+u_2^2) \qquad M^2_{1,2}=\frac{g^2}{2}(u_2^2+u_1^2)$$

$$M^2_{38}=\frac{g^2}{2}\begin{pmatrix} u_2^2+u_1^2 & \frac{1}{\sqrt{3}}(u_1^2-u_2^2) \\ \frac{1}{\sqrt{3}}(u_1^2-u_2^2) & \frac{1}{3}(4u_3^2+u_1^2+u_2^2) \end{pmatrix}$$

Muon decay from : $\mathcal{L}^{e\nu}_{\rm eff} = -\frac{2G_H}{\sqrt{2}}\sum_{a=1}^{8}\left(\overline{e_L}\,\gamma^\mu\frac{\lambda_a}{x_a}\,e_L\right)\left(\overline{\nu_L}\,\gamma_\mu\frac{\lambda_a}{x_a}\,\nu_L\right)$

$$v_\ell^2 = u_1^2+u_2^2$$

FCNC: $SU(2)_\ell$ gauge bosons ...

- But also:

$$\mathcal{L}^{\nu\nu}_{\rm eff} = -\frac{G_H}{\sqrt{2}} \sum_{a=1}^{8} \left(\overline{\boldsymbol{\nu}_L}\, \gamma_\mu \frac{\lambda_a}{x_a}\, \boldsymbol{\nu}_L\right)^2 \qquad \mathcal{L}^{ee}_{\rm eff} = -\frac{G_H}{\sqrt{2}} \sum_{a=1}^{8} \left(\overline{\boldsymbol{e}_L}\, \gamma_\mu \frac{\lambda_a}{x_a}\, \boldsymbol{e}_L\right)$$

- Constraint comes from compositeness limits:

$$v_\ell > 3\mathrm{TeV}$$

$$\begin{pmatrix} e_1 \\ e_2 \\ e_3 \end{pmatrix}_{\rm L} = V_L^{(e)} \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}_{\rm L} = \begin{pmatrix} V_{1e} & V_{1\mu} & V_{1\tau} \\ V_{2e} & V_{2\mu} & V_{2\tau} \\ V_{3e} & V_{3\mu} & V_{3\tau} \end{pmatrix}^{(e)} \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}_{\rm L}$$

FCNC?

FCNC: $SU(2)_\ell$ gauge bosons ...

Considering $\mathbf{SU(3)}_\ell$ gauge symmetry, if a symmetry between flavons η holds and

$$u_3 = u_2 = u_1$$

then

- Gauge bosons have equal masses
- They do not mix, $\lambda_a \to V^\dagger \lambda_a V$ is simply a basis redetermination of the Gell-Mann matrices
- From Fierz identities for λ matrices:

$$\mathcal{L}_{eff} = -\frac{1}{4v_\ell^2}(\overline{\mathbf{e}_\mathrm{L}}\,\lambda^a\,\gamma^\mu \mathbf{e}_\mathrm{L})(\overline{\mathbf{e}_\mathrm{L}}\,\lambda^a\,\gamma_\mu \mathbf{e}_\mathrm{L}) = -\frac{1}{3v_2^2}(\overline{\mathbf{e}_\mathrm{L}}\,\mathbb{I}\,\gamma_\mu \mathbf{e}_\mathrm{L})^2$$

That is **no FCNC**, the global $SO(8)_\ell$ symmetry acts as a custodial symmetry.

FCNC: $SU(2)_\ell$ gauge bosons ...

- In general case e.g. $\mu \to 3e$ decay:

$$\frac{\Gamma(\mu \to ee\bar{e})}{\Gamma(\mu \to e\nu_\mu \bar{\nu}_e)} \simeq \frac{1}{8}\left(\delta_\mu C(r)|U^*_{3e}U_{3\mu}|\right)^2$$

$r = 2u_3^2/v_\ell^2$, $|C(r)| < 1$. $|U_{3\mu}|$ and $|U_{3e}|$ can be almost as large as $\sin\theta_C = V_{us}$.

- The experimental limits on other LFV effects as e.g. $\tau \to 3\mu$ are much weaker.
- Also in this case $\mathbf{v}_\ell \simeq$ **6 TeV** fullfill experimental constraints.

Gauging $SU(3)_\ell \times SU(3)_e$: but triangle anomalies ?

In SM $SU(3) \times SU(2) \times U(1)$ anomalies are cancelled between quarks and leptons inside a fermion family. But for the gauge $SU(3)_\ell \times SU(3)_e$

$$\ell_{L\alpha} = \begin{pmatrix} \nu_\alpha \\ e_\alpha \end{pmatrix}_L \sim (\mathbf{3}_\ell, 1), \quad e_{R\gamma} \sim (1, \mathbf{3}_e)$$

we have triangle anomalies, both for $SU(3)_\ell$ and $SU(3)_e$

Easiest way to cancel family anomalies is to introduce opposite chirality states of the same structure:

$$\ell'_{R\alpha} = \begin{pmatrix} \nu'_\alpha \\ e'_\alpha \end{pmatrix}_R \sim (\mathbf{3}_\ell, 1), \quad e'_{L\gamma} \sim (1, \mathbf{3}_e)$$

which transform as leptons of parallel sector SM′ $SU(3)' \times SU(2)' \times U(1)'$

So with flavor bosons of $SU(3)_\ell \times SU(3)_e$ interacting with both ordinary (SM) and mirror (SM′) particles, flavor gauge anomalies are canceled

This also ealizes MFV paradigm Z.B. 1996, Z. B. and A. Rossi, 2001
Induces new FCNC phenomena like muonium disappearance: $\bar{\mu}e \to \bar{e}'\mu'$ (or $K^0 \to K^{0\prime}$ conversion) – in difference to normal FCNC, such processes have no custodial suppression and go in leading order $G_{\mathcal{F}} \approx 10^{-3} G_F$

Everything has the End... But the Wurstle has two ends: Left and Right – or Right and Left ?

Fermions and anti-fermions :

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}; \qquad u_R, \; d_R, \qquad e_R$$

B=1/3   L=1   B=1/3   L=1

$$\bar{q}_R = \begin{pmatrix} \bar{u}_R \\ \bar{d}_R \end{pmatrix}, \quad \bar{l}_R = \begin{pmatrix} \bar{\nu}_R \\ \bar{e}_R \end{pmatrix}; \qquad \bar{u}_L, \; \bar{d}_L, \qquad \bar{e}_L$$

B=-1/3   L=-1   B=-1/3   L=-1

Twin Fermions and anti-fermions :

$$q'_L = \begin{pmatrix} u'_L \\ d'_L \end{pmatrix}, \quad l'_L = \begin{pmatrix} \nu'_L \\ e'_L \end{pmatrix}; \qquad u'_R, \; d'_R, \qquad e'_R$$

B′=1/3   L′=1   B′=1/3   L′=1

$$\bar{q}'_R = \begin{pmatrix} \bar{u}'_R \\ \bar{d}'_R \end{pmatrix}, \quad \bar{l}'_R = \begin{pmatrix} \bar{\nu}'_R \\ \bar{e}'_R \end{pmatrix}; \qquad \bar{u}'_L, \; \bar{d}'_L, \qquad \bar{e}'_L$$

B′=-1/3   L′=-1   B′=-1/3   L′=-1

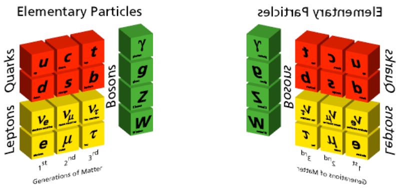
$$(\bar{u}_L Y_u q_L \bar{\phi} + \bar{d}_L Y_d q_L \phi + \bar{e}_L Y_e l_L \phi) + (u_R Y_u^* \bar{q}_R \phi + d_R Y_d^* \bar{q}_R \bar{\phi} + e_R Y_e^* \bar{l}_R \bar{\phi})$$
$$(\bar{u}'_L Y'_u q'_L \bar{\phi}' + \bar{d}'_L Y'_d q'_L \phi' + \bar{e}'_L Y'_e l'_L \phi') + (u'_R Y'^*_u \bar{q}'_R \phi' + d'_R Y'^*_d \bar{q}'_R \bar{\phi}' + e'_R Y'^*_e \bar{l}'_R \bar{\phi}')$$

Mirror Parity PZ_2 $(L, R \to R, L)$: $\quad Y' = Y^* \quad \underline{B - B' \to B - B'}$

$SU(3) \times SU(2) \times U(1) \quad + \quad SU(3)' \times SU(2)' \times U(1)'$

$G \times G'$

Regular world — Mirror world



- Two identical gauge factors, e.g. $SU(5) \times SU(5)'$, with identical field contents and Lagrangians: $\mathcal{L}_{\rm tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\rm mix}$
- Exact parity $G \to G'$: no new parameters in dark Lagrangian $\mathcal{L}'$
- MM is dark (for us) and has the same gravity
- MM is identical to standard matter, (asymmetric/dissipative/atomic) but realized in somewhat different cosmological conditions: $T'/T \ll 1$.
- New interactions between O & M particles $\mathcal{L}_{mix}$

Since 1932, neutrons make 50% of mass in our bodies ...

Neutrons are stable in basic nuclei but decay in free state: $n \to p e \overline{\nu}_e$

... and in some (β^- unstable) nuclei

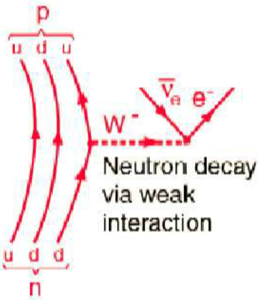
... or can be even created in other (β^+ unstable) nuclei

Fermi V-A Theory – Standard Model (SM)
conserving baryon number

$$\frac{G_V}{\sqrt{2}}\ \overline{u}(1-\gamma^5)\gamma^\mu d\ \ \overline{\nu}_e(1-\gamma^5)\gamma_\mu e \quad + \text{h.c.}$$

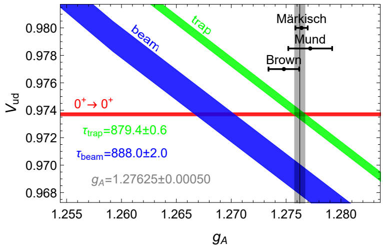
$$\frac{G_V}{\sqrt{2}}\ \overline{p}(1-g_A\gamma^5)\gamma^\mu n\ \ \overline{\nu}_e(1-\gamma^5)\gamma_\mu e \quad + \text{h.c.}$$

$$G_V = G_F\,|V_{ud}|\ \text{(CVC)} \quad \& \quad g_A \simeq 1\ \text{(PCAC)}$$



Yet, we do not know well enough its decay features and lifetime

$|V_{ud}|$ from free neutron decays



$$G_F^2|V_{ud}|^2 = \frac{K/\ln 2}{\mathcal{F}_n\tau_n(1+3g_A^2)(1+\Delta_R)}$$

$$\mathcal{F}_n = f_n(1+\delta'_R)$$

β–asymmetry: $g_A = 1.27625(50)$

$$|V_{ud}|_{\rm trap} = 0.97327(32)_{g_A}(33)_{\tau_{\rm trap}}(10)_{\Delta_R} = 0.97327(47)$$

... not yet competitive with $0^+ - 0^+$:

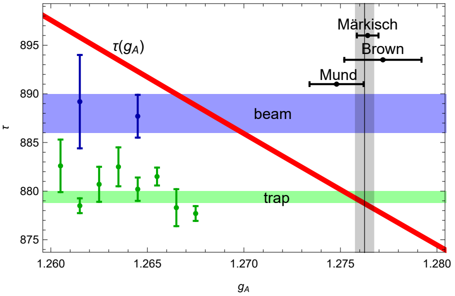
$$|V_{ud}| = 0.97370(10)_{\mathcal{F}t}(10)_{\Delta_R} = 0.97370(14)$$

$\tau_{\rm trap}$ is compatible with $\mathcal{F}t$-measurements

... and $\tau_{\rm beam}$ is incompatible

but β-ν asymmetry measurements: $g_A = 1.2677(28)$ Werner Heil talk

τ_n vs. β-asymmetry



$g_A = 1.27625(50)$

$\tau_{\rm beam} = 888.0 \pm 2.0$ s

$\tau_{\rm trap} = 879.4 \pm 0.6$ s

Free neutron decay:

$$G_V^2 = \frac{K/\ln 2}{\mathcal{F}_n \tau_n (1+3g_A^2)(1+\Delta_R)}$$

$0^+ - 0^+$ decays:

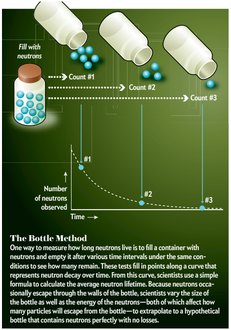
$$G_V^2 = \frac{K}{2\mathcal{F}t\,(1+\Delta_R)}$$

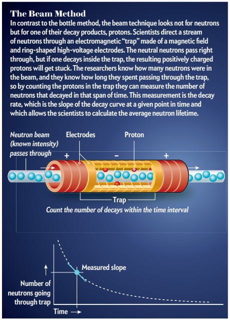
$$\tau_n = \frac{2\mathcal{F}t}{\mathcal{F}_n(1+3g_A^2)} = \frac{5172.0(1.1)}{1+3g_A^2}\ \mathrm{s}$$

G_V and Δ_R cancel out even in BSM $G_V \neq G_F|V_{ud}|$: $g_A = -G_A/G_V$

$g_A = 1.27625(50) \longrightarrow \tau_n^{\rm theor} = 878.7 \pm 0.6$ s $\approx \tau_{\rm trap}$

Two methods to measure the neutron lifetime



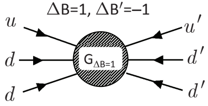


$\tau_{\rm trap} = \tau_n^{\rm theor}$ neutron total lifetime is as predicted by SM

$\tau_{\rm beam} > \tau_n^{\rm theor}$ neutron decay not always produces a proton (at least in beam experiments) – some neutrons decay in invisible channel – when magnetic field is large ($\sim$ few Tesla)

Neutron – mirror neutron mixing

Effective operator $\frac{1}{M^5}(udd)(u'd'd') \quad \to \quad$ mass mixing $\epsilon n C n' + \mathrm{h.c.}$
violating B and B' – but conserving $B - B'$



$$\epsilon = \langle n|(udd)(u'd'd')|\bar{n}'\rangle \sim \frac{\Lambda^6_{\rm QCD}}{M^5} \sim \left(\frac{10\ \rm TeV}{M}\right)^5 \times 10^{-15}\ \rm eV$$

Key observation: *$n - \bar{n}'$ oscillation cannot destabilise nuclei:*
$(A, Z) \to (A-1, Z) + n'(p'e'\bar{\nu}')$ forbidden by energy conservation
(In principle, it can destabilise Neutron Stars – talk of Mannarelli)

Even if $m_n = m_{n'}$, $n - \bar{n}'$ oscillation can be as fast as $\epsilon^{-1} = \tau_{n\bar{n}'} \sim 1$ s, without contradicting experimental and astrophysical limits.
(c.f. $\tau_{n\bar{n}'} > 2.5 \times 10^8$ s for neutron – antineutron oscillation)

Neutron disappearance $n \to \bar{n}'$ and regeneration $n \to \bar{n}' \to n$

Oscillations in non-degenerate $n - n'$ system

Consider $n - n'$ system with $\Delta m = m'_n - m_n \sim 10^2 \div 10^3$ neV and $\epsilon \sim (1\,\mathrm{TeV}/M)^5 \times 10^{-10}$ eV

Hamiltonian of (n_+, n_-, n'_+, n'_-) system ($\pm$ for 2 spin states)
decay width Γ_n is the same for all states

$$H = \begin{pmatrix} m_n - |\mu_n B| & 0 & \varepsilon & 0 \\ 0 & m_n + |\mu_n B| & 0 & \varepsilon \\ \varepsilon & 0 & m_{n'} & 0 \\ 0 & \varepsilon & 0 & m_{n'} \end{pmatrix},$$

$$m'_n = m_n + \Delta m, \quad \Omega_B = |\mu_n B| = (B/1\,\mathrm{T}) \times 60 \text{ neV}$$

In small magnetic field ($B \approx 0$) $n - n'$ mixing angles is $\theta_0 \approx \frac{\epsilon}{\Delta m}$.

$n - n'$ conversion probability is $P_{nn'} \approx \theta_0^2 \sim 10^{-6}$ or perhaps larger

In large magnetic field, mixing increases for $+$ or $-$ polarization:

$\tan 2\theta_B^{\pm} = \frac{2\varepsilon}{\Delta m \pm \Omega_B}$ Resonance effect like MSW
maximal oscillation if $\Delta m \pm \Omega_B \to 0$

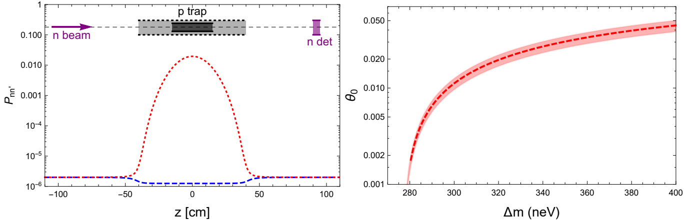
Beam Experiments

$n - n'$ conversion probability depends on magn. field in proton trap

$$N_n = P^{\rm tr}_{nn} L \int_A da \int dv\, I(v)/v \quad \text{and} \quad N_{n'} = P^{\rm tr}_{nn'} L \int_A da \int dv\, I(v)/v$$

$$P_{nn} = 1 - P_{nn'} \quad \longrightarrow \quad N_n + N_{n'} = \text{Const.}$$

Both $n \to pe\bar{\nu}$ and $n' \to p'e'\bar{\nu}'$ decays have equal rates.



$$\dot{N}_p = e_p \Gamma_\beta P^{\rm tr}_{nn} L \int_A da \int dv \frac{I(v)}{v}, \qquad \dot{N}_\alpha = e_\alpha \bar{v} P^{\rm det}_{nn} \int_A da \int dv \frac{I(v)}{v}$$

$$\tau_{\rm beam} = \left(\frac{e_p L}{e_\alpha \bar{v}}\right)\left(\frac{\dot{N}_\alpha}{\dot{N}_p}\right) = \frac{P^{\rm det}_{nn}}{P^{\rm tr}_{nn}} \tau_n$$

Experiments with material traps

Trap experiments store UCN for a time t and compare amount of survived UCN with initial one: $N_{\rm surv}(t)/N_{\rm in} = \exp(-\Gamma_{\rm st}\, t)$

For determining τ_n, one has to subtract the UCN Iregular ss rates:
$\tau_n^{-1} = \Gamma_{\rm st} - \Gamma_{\rm loss}; \quad \Gamma_{\rm loss} = \langle P_{\rm loss} f_{\rm wall} \rangle$.

In experiments with material traps (magnetic field is small).
$\Gamma_{\rm st}$ is measured for different $f_{\rm wall}$ linearly extrapolating to $f_{\rm wall} \to 0$

In fact, limit $P_{\rm loss} < 2 \times 10^{-6}$ comes from Serebrov 2005
which reports $\tau_n = 778.5 \pm 0.8$ s

Other trap experiments estimate about 2 times bigger $P_{\rm loss}$ and about about 2 s bigger lifetimes.

I take $P_{nn'} = \theta_0^2 \leq 10^{-6}$ .... but for $\Delta m > 60$ neV larger θ_0 are allowed
(This could explain anomalous UCN loses in Beryllium and graphite traps)

Average of material trap experiments: $\tau_{\rm mat} = 879.4 \pm 0.6$ s,
the UCN $n \to n'$ losses are subtracted (together with regular losses)

Experiments with magnetic traps

Large surface magnetic field (~ 1 T with exponential gradient) reflects the UCN of one polarization
(and about 10 G holding field protects the UCN from depolarization)

Also store UCN for a time t and compare amount of survived UCN with initial one: $N_{\rm surv}(t)/N_{\rm in} = \exp(-\Gamma_{\rm st} t)$

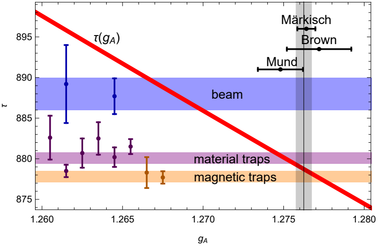
For determining τ_n, estimate the UCN loss rates and subtract them: $\tau_n^{-1} = \Gamma_{\rm st} - \Gamma_{\rm loss}$;

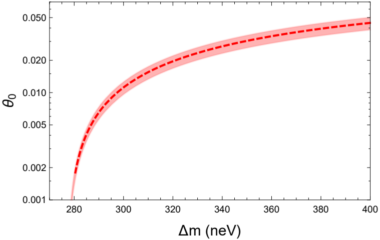
The UCN losses are estimated to be almost irrelevant: about 0.2 s correction But losses per scattering are not measured and only depolarisation rate is controlled:
On the other hand, $\Gamma_{\rm loss} = \langle f_{\rm scat} P_{nn'} \rangle$ with $P_{nn'} \sim 10^{-6}$ would give $1 \div 2$ s correction.

Magnetic trap τ_n, in view of $n - n'$ possibility, can be *underestimated*.

Average of magnetic trap experiments: $\tau_{\rm magn} = 877.8 \pm 0.7$ s ,

where the UCN $n \to n'$ losses *are not* subtracted ...





$\tau_n^{\rm SM} = 878.7 \pm 0.6$ s $\qquad \tau_{\rm beam} = 888.0 \pm 2.0$ s $\quad (4.4.\sigma)$

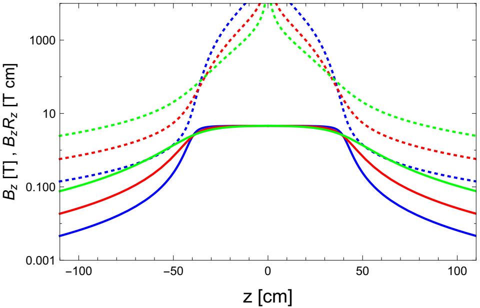
$\tau_n^{\rm SM} = 878.7 \pm 0.6$ s $\qquad \tau_{\rm trap} = 879.4 \pm 0.6$ s $\quad$ (compatible)

$\tau_{\rm mat} = 880.0 \pm 0.7$ s, $\quad \tau_{\rm magn} = 877.8 \pm 0.7$ s (2.3σ discrepancy)

So experimentally we have $\quad \tau_{\rm magn} < \tau_{\rm mat} = \tau_n = \tau_\beta < \tau_{\rm beam}$

this is possible in my scenario $\quad$ So far so Good!

Adiabatic or non-adiabatic (Landau-Zener) conversion ?



$$P^{\rm tr}_{nn'} \approx \frac{\pi}{4}\xi \simeq 10^{-2}\left(\frac{2\ \mathrm{km/s}}{v}\right)\left(\frac{P^0_{nn'}}{10^{-6}}\right)\left(\frac{R_{\rm res}\,B_{\rm res}}{10\ \mathrm{cm\,T}}\right)$$

$R(z) = (d\ln B/dz)^{-1}$ – characterises the magnetic field gradient at the resonance

Dark matter Factory ?

If my hypothesis is correct, a simple solenoid with magnetic fields $\sim$ Tesla can be very effective machines that transform neutrons into dark matter.

Simple experiments could test this

Adiabatic conditions can be improved and 50 % transformation can be achieved

$$P^{\rm tr}_{nn'} \approx \frac{\pi}{4}\xi \simeq 10^{-2}\left(\frac{2\ \rm km/s}{v}\right)\left(\frac{P^0_{nn'}}{10^{-6}}\right)\left(\frac{B_{\rm res}}{1\ \rm T}\right)\left(\frac{R_{\rm res}}{10\ \rm cm}\right)$$

ZB, "'Neutron lifetime puzzle and neutron-mirror neutron oscillation", e-Print:arXiv:1807.07906

Thank You ...

It's wonderful to be here
It's certainly a thrill
You're such a lovely audience ...

I hope you have enjoyed the show
I'm sorry but it's time to go
It's getting very near the end
I'd like to thank you once again