The Neutron Decay Problems and New Physics

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Neutrons: since 1932 they make 50% of mass in our bodies ...

Neutrons are closely mass degenerate with the proton (in the SM $n = udd$, $p = uud$) since B is conserved in the SM, n and p both are Dirac particles with $B = 1$)

Neutrons are stable in basic nuclei but decay in free state: $n \to pe\bar{\nu}_e$
... and decay also in (β^- unstable) nuclei
... and can be even born in (β^+ unstable) nuclei: $p \to ne^+\nu_e$

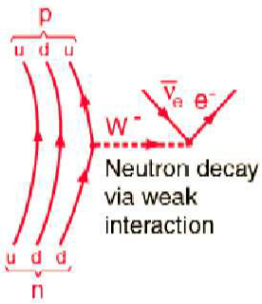
Fermi V-A Theory → *Standard Model*

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

$$G_V = G_F\,|V_{ud}|, \quad G_F = G_\mu \qquad + \text{CKM mixing}$$

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

$$g_V = 1 \text{ (CVC)} \quad \& \quad g_A \simeq 1.2 \text{ (PCAC)}$$



Yet, we do not know all its secrets in depth ...

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

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

$$\mathbf{V}_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \qquad 3 \times 3 \text{ unitary}$$

First row $\quad |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \quad \ldots \; |V_{ub}|^2 \simeq 10^{-5}$

Cabibbo universality: $\quad |V_{ud}|^2 + |V_{us}|^2 = 1 \quad \cos^2\theta_C + \sin^2\theta_C = 1$

... is testable at the present experimental accuracy

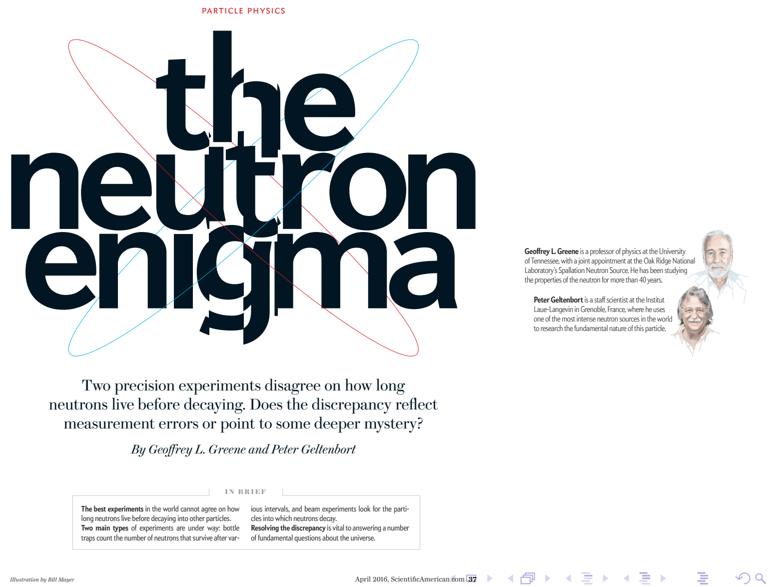
Semileptonic $K\ell 3$ decays ($K \to p \ell \nu$) : $\quad f_+(0)|V_{us}| = 0.21654(41)$

Leptonic $K\mu 2$ decays (K/π ratio): $\quad \left| \frac{V_{us}}{V_{ud}} \right| \frac{f_{K^\pm}}{f_{\pi^\pm}} = 0.27599(38)$

$f_+(0)$ and f_K/f_π from Lattice QCD

$|V_{ud}|$ – from neutron decay and $n \leftrightarrow p$ transitions ($\beta^\pm$) in nuclei

The neutron enigma ...



PARTICLE PHYSICS

the neutron enigma

Two precision experiments disagree on how long neutrons live before decaying. Does the discrepancy reflect measurement errors or point to some deeper mystery?

By Geoffrey L. Greene and Peter Geltenbort

Geoffrey L. Greene is a professor of physics at the University of Tennessee, with a joint appointment at the Oak Ridge National Laboratory's Spallation Neutron Source. He has been studying the properties of the neutron for more than 40 years.

Peter Geltenbort is a staff scientist at the Institut Laue-Langevin in Grenoble, France, where he uses one of the most intense neutron sources in the world to research the fundamental nature of this particle.

IN BRIEF

The best experiments in the world cannot agree on how long neutrons live before decaying into other particles.

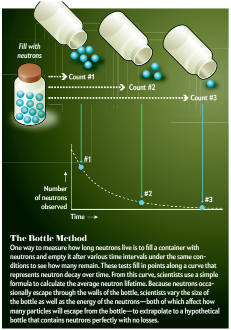
Two main types of experiments are under way: bottle traps count the number of neutrons that survive after various intervals, and beam experiments look for the particles into which neutrons decay.

Resolving the discrepancy is vital to answering a number of fundamental questions about the universe.

Illustration by Bill Mayer

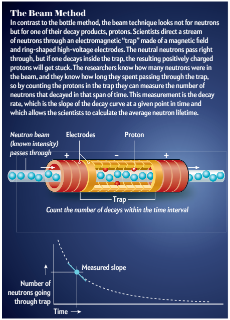
April 2016, ScientificAmerican.com 37

How the neutron lifetime can be measured?



The Bottle Method

One way to measure how long neutrons live is to fill a container with neutrons and empty it after various time intervals under the same conditions to see how many remain. These tests fill in points along a curve that represents neutron decay over time. From this curve, scientists use a simple formula to calculate the average neutron lifetime. Because neutrons occasionally escape through the walls of the bottle, scientists vary the size of the bottle as well as the energy of the neutrons—both of which affect how many particles will escape from the bottle—to extrapolate to a hypothetical bottle that contains neutrons perfectly with no losses.



The Beam Method

In contrast to the bottle method, the beam technique looks not for neutrons but for one of their decay products, protons. Scientists direct a stream of neutrons through an electromagnetic "trap" made of a magnetic field and ring-shaped high-voltage electrodes. The neutral neutrons pass right through, but if one decays inside the trap, the resulting positively charged protons will get stuck. The researchers know how many neutrons were in the beam, and they know how long they spent passing through the trap, so by counting the protons in the trap they can measure the number of neutrons that decayed in that span of time. This measurement is the decay rate, which is the slope of the decay curve at a given point in time and which allows the scientists to calculate the average neutron lifetime.

$\tau_{\rm trap} = \Gamma_{\rm tot}^{-1}$ neutron total decay width (neutron disappearance)

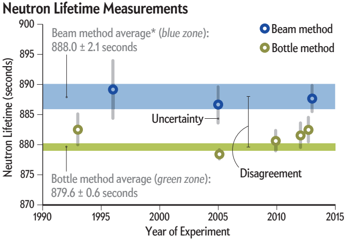
$\tau_{\rm beam} = \Gamma_{n\to pe\bar\nu}^{-1}$ neutron β-decay width (counting produced protons)

$\Gamma_\beta = \Gamma_{\rm tot} \times {\rm Br}(n \to pe\bar\nu) \quad \longrightarrow \quad \tau_{\rm trap} < \tau_{\rm beam}$

In SM ${\rm Br}(n \to p) = 1$ two methods must give same results!

Invisible decay channel ? $\tau_{\rm trap} = \tau_{\rm beam} \times {\rm Br}(n \to pe\bar\nu)$

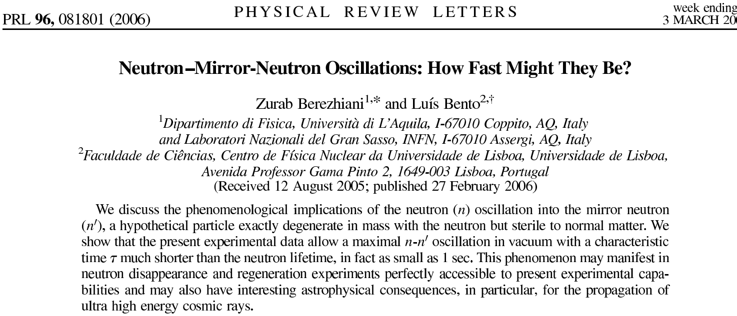
But the two ways do to meet ...



Quest for New Physics?

A few theorists have taken this notion seriously. Zurab Berezhiani of the University of L'Aquila in Italy and his colleagues have suggested such a secondary process: a free neutron, they propose, might sometimes transform into a hypothesized "mirror neutron" that no longer interacts with normal matter and would thus seem to disappear. Such mirror matter could contribute to the total amount of dark matter in the universe. Although this idea is quite stimulating, it remains highly speculative. More definitive confirmation of the divergence between the bottle and beam methods of measuring the neutron lifetime is necessary before most physicists would accept a concept as radical as mirror matter.

Neutron – mirror neutron oscillation



PRL **96,** 081801 (2006) PHYSICAL REVIEW LETTERS week ending
3 MARCH 20

Neutron–Mirror-Neutron Oscillations: How Fast Might They Be?

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We discuss the phenomenological implications of the neutron (n) oscillation into the mirror neutron (n'), a hypothetical particle exactly degenerate in mass with the neutron but sterile to normal matter. We show that the present experimental data allow a maximal n-n' oscillation in vacuum with a characteristic time τ much shorter than the neutron lifetime, in fact as small as 1 sec. This phenomenon may manifest in neutron disappearance and regeneration experiments perfectly accessible to present experimental capabilities and may also have interesting astrophysical consequences, in particular, for the propagation of ultra high energy cosmic rays.

Present situation ... four players in the game

Beam experiments (×2) $\tau_{\rm beam} = 888.0 \pm 2.0$ s

Byrne et al. Europhys. L. 33 (1996); Yue et al. PRL 111 (2013)

Material traps (×6) $\tau_{\rm mat} = 880.1 \pm 0.7$ s

Mampe et al. JETP L. 57 (1993); Serebrov et al., PLB 605, 72 (2005); Pichlmaier et al. PLB 693 (2010); Steyerl et al. PRL 63 (2012); Arzumanov et al., JETP L. 95 (2012); Serebrov et al. PRC 97 (2018)

Magnetic traps (×3) $\tau_{\rm magn} = 878.8 \pm 0.3$ s

Ezhov et al., JETP L. 107 (2018); Pattie et al. (UCNτ), Science 360 (2018); Gonzalez et al. (UCNτ), PRL 127 (2021)

$3.3\,\sigma$ tension between $\tau_{\rm mat}/\tau_{\rm magn}$ $\Delta\tau = 2.3 \pm 0.7$ s

Trap (mat+magn) average $\tau_{\rm trap} = 878.5 \pm 0.5$ s

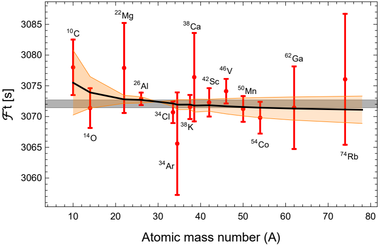
$4.5\,\sigma$ tension between $\tau_{\rm beam}/\tau_{\rm trap}$ $\Delta\tau = 9.5 \pm 2.1$ s

- SM itself predicts

$\tau_n \equiv \tau_{n\to pe\bar\nu} = 878.7 \pm 1.5$ s agrees with $\tau_{\rm trap} = 878.5 \pm 0.5$ s

Superallowed $0^+ - 0^+$ nuclear transitions
(pure Fermi – g_A independent)

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



Hardy & Towner, 2015

$\overline{\mathcal{F}t} = 3072.07(72)$ s

2020: $\to 3072.24(1.85)$ s

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

in SM $\quad G_V = G_F|V_{ud}|$

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

Short-distance (transition independent) electroweak corrections

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

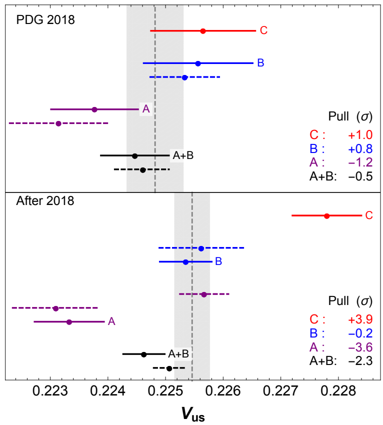
$$|V_{ud}| = 0.97420(10)_{\mathcal{F}t}(18)_{\Delta_R} = 0.97420(21) = \cos\theta_C$$

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

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

Cabibbo Angle Anomaly:

Belfatto, Beradze and Z.B, EPJ C 80, 149 (2020) arXiv:1906.02714



$$V_{ud}^2 + V_{us}^2 = 1 \; \ldots |V_{ub}|^2 \simeq 10^{-5}$$

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

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

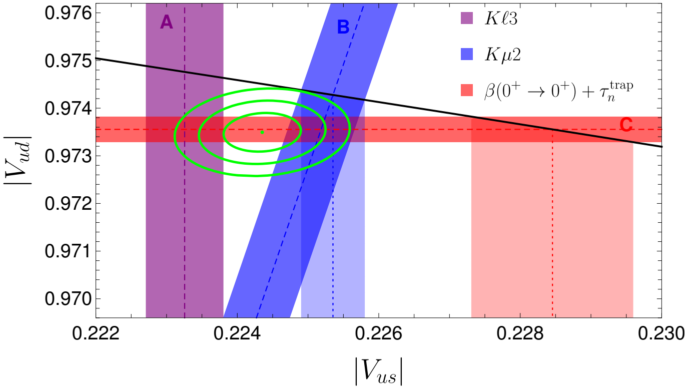
Post 2018:
A & B: FLAG'19 + MILC'19
C: Δ_R Seng et al '18

A ($K \to \ell 3$): $K \to \pi \ell \nu \longrightarrow |V_{us}| = \sin\theta_C$

B ($K \to \mu 2$): K/π ratio $\longrightarrow |V_{us}/V_{ud}| = \tan\theta_C$

C ($0^+ - 0^+$ transitions) : $\longrightarrow |V_{ud}| = \cos\theta_C$

Cabibbo Anomaly updated – O. Fischer et al., arXiv: 2109.06065



If CKM unitarity is assumed – strong discrepancy between
A: $|V_{us}| = \sin\theta_C$ B: $|V_{us}/V_{ud}| = \tan\theta_C$ C: $|V_{ud}| = \cos\theta_C$

Quest for New Physics at the scale of few TeV?
vector-like quarks, lepton flavor-changing gauge bosons, etc.

Neutron lifetime in SM: $\tau_n - g_A$ relation

G_V from free neutron decay

from $0^+ - 0^+$

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

$$\tau_n = \frac{2\mathcal{F}t}{\mathcal{F}_n(1+3g_A^2)} = \frac{5172.1(1.1 \to 2.8)}{1+3g_A^2}\ \mathrm{s}$$

Czarnecki et al. 2018

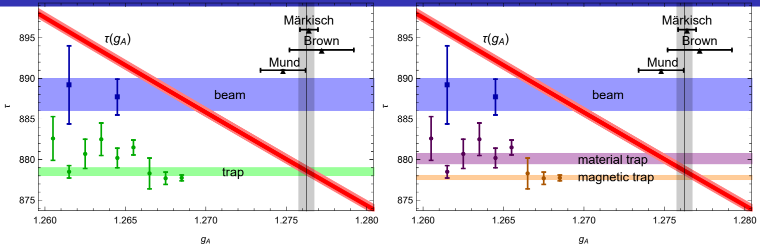
G_V and Δ_R cancel out (even in BSM $G_V \neq G_F|V_{ud}|$, $g_A = -G_A/G_V$)

$$g_A = 1.27625(50) \quad \longrightarrow \quad \tau_n^{\mathrm{theor}} = 878.7 \pm (0.6 \to 1.5)\ \mathrm{s} \quad \approx \tau_{\mathrm{trap}}$$

g_A – average from Percheo I/II and UCNA experiments

Status of the four players in the game:

Updated Fig.7 of Belfatto, Beradze and Z.B, arXiv:1906.02714



$\tau_n^{\rm theor} = 878.7 \pm 1.5$ s $\tau_{\rm trap} = 878.5 \pm 0.5$ s   (compatible)

$\tau_{\rm beam} = 888.0 \pm 2.0$ s (4.5σ)

$\tau_{\rm mat} = 880.1 \pm 0.7$ s $\tau_{\rm magn} = 877.8 \pm 0.3$ s $(3.3\sigma$ discrepancy)

So for 4 players we have $\tau_{\rm magn} < \tau_n^{\rm theor} < \tau_{\rm mat} \ll \tau_{\rm beam}$

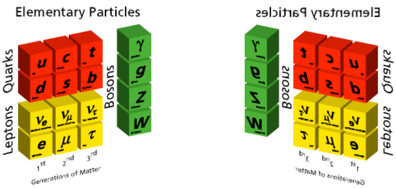
Not only one neutron state n
– there should be also a nearly mass degenerate "sterile neutron" n'

From where "dark" n' can come?
It can be *ad hoc* elementary particle casually degenerate with n ... or

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

$$G \times G'$$

Regular world　　　Mirror world

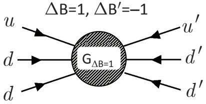


- Two identical gauge factors, e.g. $SU(5) \times SU(5)'$, with identical field contents and Lagrangians: $\mathcal{L}_{\rm tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\rm mix}$
- Exact parity $G \leftrightarrow G'$: no new parameters in dark Lagrangian $\mathcal{L}'$
- MM is dark (for us) and has 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 $\mathcal{L}_{mix}$
- $G \leftrightarrow G'$ can be softly broken: small splittings between O and M masses

Neutron – mirror neutron mixing

Z.B. and Bento, PRL 96, 081801 (2006), hep-ph/0507031

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 $B - B'$



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

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

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)

Search via disappearance $n \to \bar{n}'$ and regeneration $n \to \bar{n}' \to n$

$n - n'$ mixing

Mass mixing two states, n and n'

$$H = \begin{pmatrix} m_n & \epsilon \\ \epsilon & m'_n \end{pmatrix} \longrightarrow H_{\rm diag} = \begin{pmatrix} m_1 & 0 \\ 0 & m_2 \end{pmatrix}$$

$n_1 = cn - sn'$, $n_2 = sn + cn'$ $c = \cos\theta$, $s = \sin\theta$ $\tan 2\theta = \frac{2\epsilon}{2\delta}$

$2\delta = m_{n'} - m_n \longrightarrow \Delta m = m_2 - m_1 = 2\sqrt{\delta m^2 + \epsilon^2}$

More generally: with transitional dipole moments and matter

$$H = \begin{pmatrix} m_n + \vec{\mu}_n \vec{B} + V & \epsilon + \vec{\kappa}(\vec{B} + \vec{B}') + \vec{\rho}(\vec{E} + \vec{E}') \\ \epsilon + \vec{\kappa}(\vec{B} + \vec{B}') + \vec{\rho}(\vec{E} + \vec{E}') & m_{n'} + \vec{\mu}_{n'} \vec{B}' + V' \end{pmatrix}$$

One could consider the case $n' = \bar{n}$ (antineutron) - then
$m_{\bar{n}} = m_n$, $\mu_{\bar{n}} = -\mu_n$ (CPT) and $\kappa, \rho = 0$ (Lorentz inv.) → $\Delta m = 2\epsilon$
– but exp. limits $\varepsilon^{-1} > 10^8$ s (direct & nuclear stability) makes it unfit

For $n' \neq \bar{n}$ (mirror neutron) $m_{n'} = m_n$, $\mu_{n'} = \mu_n$ can be guaranteed by exact $G \leftrightarrow G'$ parity – which allows transitional moments $\kappa, \rho \neq 0$

Generically $G \leftrightarrow G'$ parity can be softly broken → $n - n'$ mass splitting.
Three situations for Δm:

small ($<$ few neV) – intermediate (few μeV) – large ($\sim$ MeV)

Free Neutrons: Where to find Them ?

Neutrons are making 1/7 fraction of baryon mass in the Universe.
But most of neutrons bound in nuclei .... where $n - n'$ is ineffective

$n \to n'$ can take place for free neutrons but it might be suppressed by some environmental factors (matter, magnetic field) or simply by some mass splitting between $n - n'$

Free neutrons are present only in

- Reactors and Spallation Facilities (experiments are looking for)
- Cosmic Rays ($n - n'$ in TA /Auger) – $\Delta m \simeq 0$ and $\epsilon^{-1} < 100$ s
- BBN epoch (injection $n' \to \bar{n}$ can help Lithium problem)

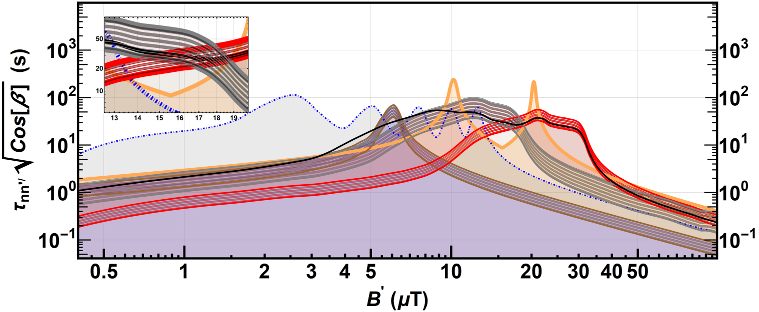
– Transition $n \to n'$ can take place in Neutron Stars – conversion of NS into mixed NS – limits $\epsilon^{-1} > 1$ s or $\epsilon^{-1} < 10^{-5}$ s (independent of Δm)

– Underlying BSM physics of $n - n'$ can be at the origin of co-baryogenesis in both O and M sectors, with $\Omega_{B'}/\Omega_B \simeq 5$
Sakharov conditions: $\Delta B, \Delta B' = 1$, CP + automatic out of equilibrium

For some parameters $n - n'$ can be relevant for neutron lifetime puzzle !

UCN experiments $n - \bar{n}$ oscillation: very small Δm

Several experiments searched for $n \to n'$ with the UCN traps.
Some show anomalies: non-zero asymmetries $\pm B$



Ban... PRL 99, 161603 (2007); Serebrov... PLB 663, (2008); Altarev... PRD 80 (2009); Bodek... NIM A611 (2009); Serebrov... NIM A611 (2009); Z.B. & Nesti EPJ C72 (2012); Berezhiani... EPJ C78 (2018); Abel... PLB 812 (2021) – collected in N. Ayres et al. arXiv:2111.02794

Latter exp. can exclude $\varepsilon^{-1} < 100$ s for $\Delta m/B'$ up to 200 μT

Experiments with material traps $B \simeq 0.5$ G

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 loss rates:
$\tau_n^{-1} = \Gamma_{\rm st} - \Gamma_{\rm loss}; \quad \Gamma_{\rm loss} = \langle P_{\rm loss} f_{\rm wall} \rangle$.

For $\Delta m < 60$ neV, $n - n'$ oscillation with $P_{nn'} \sim 10^{-6}$ between wall collisions can contribute as $\sim$ second in storage time

$$H = \begin{pmatrix} m_n + \mu_n B & \epsilon \\ \epsilon & m_n' = m_n + 2\delta \end{pmatrix} \longrightarrow \begin{pmatrix} m_1 \simeq m_n & 0 \\ 0 & m_2 = m_1 + \Delta m \end{pmatrix}$$

$\theta_0 \simeq \epsilon/\delta < 10^{-3}$ for $B \simeq 0.5$ G $\quad (|\mu_n B| \ll \delta) \quad P_{nn'} \simeq \theta_0^2$

$\Gamma_{\rm st}$ is measured for different $f_{\rm wall}$ linearly extrapolating to $f_{\rm wall} \to 0$

$n \to n'$ UCN losses are subtracted (together with any regular losses)
$P_{nn'} < P_{\rm loss} < 2 \times 10^{-6}$ from Serebrov '05 reporting $\tau_n = 778.5 \pm 0.8$ s
Other exps. estimate about twice as bigger $P_{\rm loss}$ and about 2 s bigger τ_n's

$P_{nn'} = \theta_0^2 < 10^{-6}$ .... for $\Delta m \leq 60$ neV or so

Average of material trap experiments: $\quad \tau_{\rm mat} = 880.1 \pm 0.7$ s,

Experiments with magnetic traps: $B \simeq 1$ T

Large surface magnetic field (~ 1 T with exponential gradient) reflects the UCN of one polarization (10 G holding field prevents UCN 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, UCN loss rates to be subtracted: $\tau_n^{-1} = \Gamma_{\rm st} - \Gamma_{\rm loss}$;

The UCN losses are estimated to be irrelevant: 0.2 s correction

$$H = \begin{pmatrix} m_n + \mu_n B & \epsilon \\ \epsilon & m'_n = m_n + 2\delta \end{pmatrix} \longrightarrow \begin{pmatrix} m_1^B \simeq m_n & 0 \\ 0 & m_2 = m_1 + \Delta m \end{pmatrix}$$

$\theta_B \simeq \frac{\epsilon/}{2\delta - |\mu_n B|} > \theta_0$ – resonant enhancement in magnetic field $B \sim 1$ T with $P_{nn'} \sim 10^{-6}$ could give $1 \div 2$ s contribution to τ_n

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

Average of magnetic trap experiments: $\tau_{\rm magn} = 877.8 \pm 0.3$ s

$\tau_n^{\rm th} = \tau_{\rm mat} > \tau_{\rm magn}$ can be potentially explained by $n \to n'$ losses
But $\tau_{\rm beam} \gg \tau_{\rm mat}$ cannot be explained !

Very large $\Delta m \sim$ MeV and neutron dark decay

$m_n > m_{n'}$ with $m_n - m'_n = \Delta m \simeq 1$ MeV

Z.B. talk at the INT Workshop, Seattle, Oct. 2017 – $n' =$ mirror neutron
Fornal and Grinstein, arXiv:1801.01124 – n' is ad hoc elementary fermion

$$\begin{pmatrix} m_n + \mu_n B & \epsilon + \kappa(B+B') \\ \epsilon + \kappa(B+B') & m'_n + \mu_{n'} B' \end{pmatrix} \to \begin{pmatrix} m_1 + \mu_n B & \theta\mu_n(B+B') \\ \theta\mu_n(B+B') & m_2 + \mu_{n'} B' \end{pmatrix}$$

$\theta \simeq \frac{\epsilon}{\delta}$ – induces non-diagonal transitional moment between mass eigenstates n_1 and n_2: $\mu_{nn'} \sim \theta\mu_n$ (even if $\kappa = 0$)

Hence 'invisible' decay(s) $n \to n' + \gamma(\gamma')$ (in reality $n_1 \to n_2$ decays)

$$\Gamma(n \to n'\gamma',\gamma) = \frac{1}{8\pi}\mu_{nn'}^2 m_n^3 \left(1 - \frac{m_n'^2}{m_n^2}\right)^2 = 4\alpha^2 x^2 m_n (\Delta m/m_n)^3$$

Branching $\mathrm{Br}(n'\gamma) \simeq 10^{-2}$ can be obtained then for $x = \mu_{nn'}/\mu_n \sim 10^{-9}$

Trap method – the neutron total width: $\tau_{\rm dec}^{-1} = \Gamma_{\rm tot} = \Gamma_{\rm vis} + \Gamma_{\rm inv}$
beam method – β-decay width $\Gamma_{\rm vis}(n \to pe\bar\nu) = \tau_{\rm beam}^{-1}$

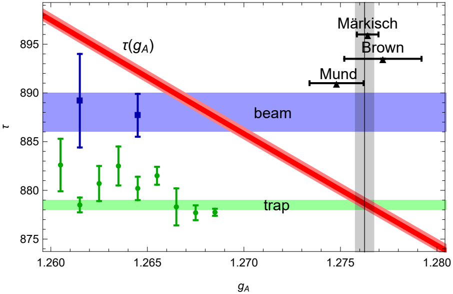
$\tau_n^{\rm th}(n \to pe\bar\nu) = \tau_{\rm beam}$ – contradicts to $\tau_n - g_A$ relation

Same for the other possibility: $n \to n'$ in traps with n' annihilating with mirror anti-gas captured in the Earth Z.B. arXiv:1602.08599

Dark decay cannot solve trap-beam lifetime puzzle: τ_n vs. β-asymmetry

$\tau_{\rm trap}^{-1} = \Gamma_{\rm tot} = \Gamma_{n\to p} + \Gamma_{n\to n'}$ and $\tau_{\rm beam}^{-1} = \Gamma_{n\to p} = {\rm Br}(n\to p) \times \tau_{\rm trap}^{-1}$

$\tau_{\rm trap} = {\rm Br}(n\to p) \times \tau_{\rm beam}$ i.e. ${\rm Br}(n\to p) \simeq 99\%$, ${\rm Br}(n\to n') \simeq 1\%$



$g_A = 1.27625(50)$

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

$\tau_{\rm trap} = 878.5 \pm 0.5$ s

$$G_V^2({\rm free}) = \frac{K/\ln 2}{\mathcal{F}_n \tau_n (1+3g_A^2)(1+\Delta_R)} \equiv G_V^2(0^+ - 0^+) = \frac{K}{2\mathcal{F}t\,(1+\Delta_R)}$$

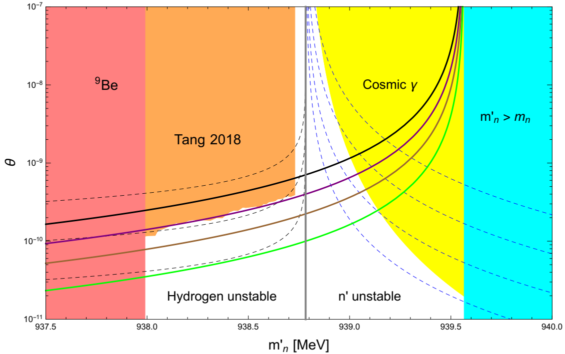
$$\tau_{n\to p}^{\rm theor} = \Gamma_{n\to p}^{-1} = \frac{2\mathcal{F}t}{\mathcal{F}_n(1+3g_A^2)} = \frac{5172.1(2.8)}{1+3g_A^2}\ {\rm s}$$

$$g_A^{\rm exp} \longrightarrow \tau_n^{\rm theor} = 878.7 \pm 1.5\ {\rm s} \approx \tau_{\rm trap} \longrightarrow {\rm Br}(n\to n') < 0.2\%$$

Minor possibility: Fierz term – tensor operators contributing β decays

Status of the Neutron Dark Decay

Z.B., LHEP 2, 118 (2019), arXiv:1812.11089



$\mathrm{Br}(n \to n'\gamma) = 0.01$ $\mathrm{Br}(n \to n'\gamma) = \mathrm{Br}(n \to n'\gamma') = 0.004$

If $m_{n'} > m_p + m_e$, DM decays $n' \to p e \bar{\nu}_e$ ($\tau = 10^{14}, 10^{15}, 10^{16}, 10^{17}$ yr)
DM decay $\tau < 10^{10}$ yr good for H0 tension ZB, Dolgov, Tkachev 2015

If $m_{n'} < m_p + m_e$, Hydrogen atom decays ($\tau = 10^{20}, 10^{21}, 10^{22}$ yr)
electron capture $e + p \to n' + \gamma$ – unstable hydrogen?? can be interesting

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

Z.B., EPJ C 79, 484 (2019)   arXiv:1807.07906

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 $\Delta m \pm \Omega_B \to 0$

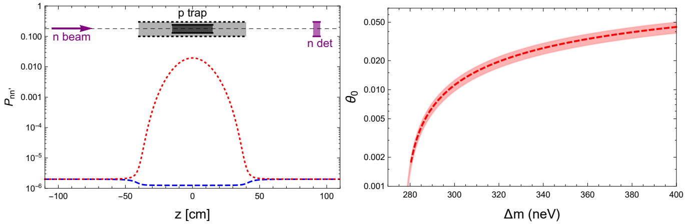
Beam Experiments

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

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

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

$n \to pe\bar\nu$ and $n' \to p'e'\bar\nu'$ decays have equal rates: $\tau_n = \tau_{n'}$



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

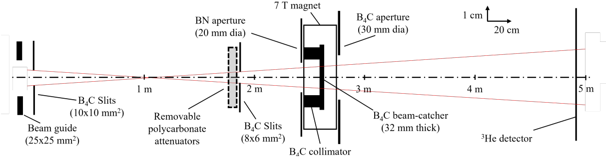
$$\tau_{\rm beam} = \left(\frac{e_p L}{e_\alpha \bar v}\right)\left(\frac{\dot N_\alpha}{\dot N_p}\right) = \frac{P^{\rm det}_{nn}}{P^{\rm tr}_{nn}}\, \tau_n$$

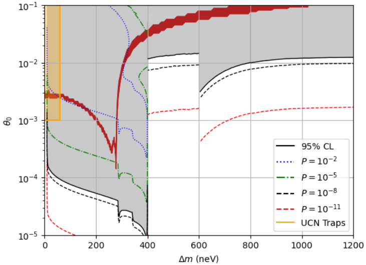
ORNL experiment

Broussard et al. arXiv:2111.05543

Testing this scenario via $n \to n' \to n$ in strong magn. fields

Difference of neutron counts between $B = 0$ and $B = 5$ T

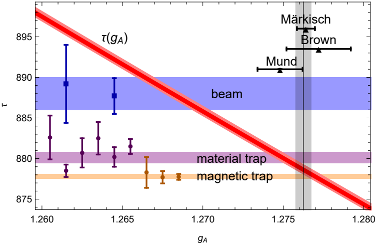




For $\Delta m \gg 1$ μeV initial state in the beam is not n but the light eigenstate $n_1 = cn - sn'$ (heavier n_2 cannot be bounced by the walls of guide)

Brief Summary

Significant discrepancies neutron lifetimes measured with different methods: beam, material traps, magnetic traps



$$\tau_{\rm mat} = 880.1 \pm 0.7 \text{ s} \qquad \tau_{\rm magn} = 877.8 \pm 0.3 \text{ s} \qquad \tau_{\rm beam} = 888.0 \pm 2.0 \text{ s} \;:$$

$$\tau_n^{\rm theor} = 878.7 \pm 1.5 \text{ s} : \qquad \tau_{\rm magn} < \tau_n^{\rm theor} < \tau_{\rm mat} \ll \tau_{\rm beam}$$

Potentiality of general case with $\Delta m > \mu$eV and transitional moments is not yet explored

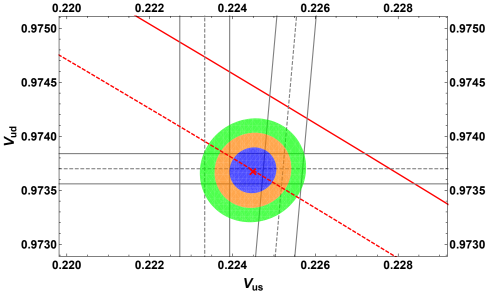
$$H = \begin{pmatrix} m_n + \vec{\mu}_n \vec{B} + V & \epsilon + \vec{\kappa}(\vec{B} + \vec{B}') + \vec{\rho}(\vec{E} + \vec{E}') \\ \epsilon + \vec{\kappa}(\vec{B} + \vec{B}') + \vec{\rho}(\vec{E} + \vec{E}') & m_{n'} + \vec{\mu}_{n'} \vec{B}' + V' \end{pmatrix}$$

Backup

Some auxiliary slides

New physics at TeV scale? extra quarks b', t'

Belfatto, Beradze and Z.B, EPJ C 80, 149 (2020) arXiv:1906.02714



CKM

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

Extra vector-like quarks
b', t' or (t', b')
with masses of few TeV

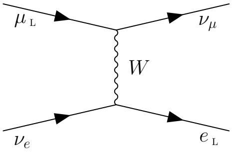
$$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2 = 1-\delta^2_{\rm CKM} \quad \dots \ \delta_{\rm CKM} \simeq |V_{ub'}| \approx 0.04$$

$$\tilde V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{pmatrix} \quad \text{is not unitary!}$$

One can reconcile A-B-C but flavor-changing, precision tests ....

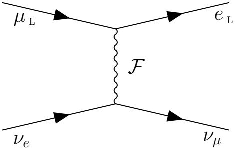
$G_F \neq G_\mu$? flavor gauge bosons at TeV scale

Belfatto, Beradze and Z.B, EPJ C 80, 149 (2020) arXiv:1906.02714



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

$v_\mathrm{w} = 174$ 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:

$$\frac{4G_\mu}{\sqrt{2}}(\overline{\nu_\mu}\gamma^\alpha\mu_L)(\overline{e_L}\gamma_\alpha\nu_e) \quad G_\mu = G_F + G_\mathcal{F} = G_F(1+\delta_\mu) \quad \delta_\mu = \left(\frac{v_\mathrm{w}}{v_\mathcal{F}}\right)^2$$

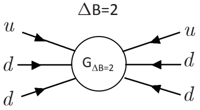
New interaction has positive interference with SM, i.e. $G_\mu > G_F$

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

Other possibilities e.g. modifying $W\ell\nu$ vertex discussed (Crivellin et al.)

Neutron–antineutron oscillation

Majorana mass of neutron $\epsilon(n^T C n + \bar{n}^T C \bar{n})$ violating B by two units comes from six-fermions effective operator $\frac{1}{M^5}(udd)(udd)$



It causes transition $n(udd) \to \bar{n}(\bar{u}\bar{d}\bar{d})$, oscillation time $\tau_{n\bar{n}} = \epsilon^{-1}$

$\epsilon \sim \frac{\Lambda^6_{\rm QCD}}{M^5} \sim \left(\frac{1~\rm PeV}{M}\right)^5 \times 10^{-25}$ eV $\quad \tau_{n\bar{n}} \sim 10^9$ s

ILL experiment: $\tau_{n\bar{n}} > 0.86 \times 10^8$ s $\longrightarrow \epsilon < 7.7 \times 10^{-24}$ eV
Key moment: *$n - \bar{n}$ oscillation destabilizes nuclei:*
$(A, Z) \to (A-1, \bar{n}, Z) \to (A-2, Z/Z-1) + \pi$'s

Nuclear stability bounds - Oxygen$\to 2\pi$ – $\tau_{\rm nucl} > 10^{32}$ yr (SK)
$\epsilon < 2.5 \times 10^{-24}$ eV $\quad \to \quad \tau > 2.7 \times 10^8$ s

Anthropic limit on $n - \bar{n}$

Scale of relevant new physics is unknown – but $\epsilon \propto M^{-5}$

Nuclear instability time against
$(A, Z) \to (A-1, \bar{n}, Z) \to (A-2, Z/Z-1) + \pi$'s scales as

$$\tau_{\rm nucl} \propto \epsilon^2 \propto M^{-10}$$

Present limit $\epsilon < 2.5 \times 10^{-24}$ eV $\quad (\tau_{\rm nucl} > 10^{32}$ yr$)$ implies

$$M > 500 \text{ TeV or so}$$

$M \simeq 100$ TeV (just factor of 5 less) would give $\tau_{\rm nucl} > 10^{25}$ yr

.. the Earth (any planet) radioactivity turns dangerous for the Life!

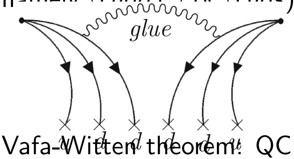
And (happily) the neutron is not elementary particle – in which case it would be allowed unsuppressed Majorana mass
But it is composite $n = (udd)$ of three quarks
– its Majorana mass can be induced only by D=9 operator $\frac{1}{M^5}(udd)^2$
Life is allowed by the structure of SM

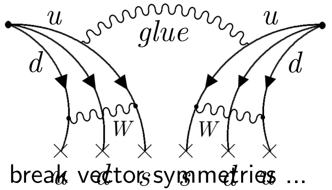
Anthropic QCD θ-term (provocation)

Z.B., EPJ C 76, 705 (2016), arXiv:1507.05478

QCD forms quark condensate $\langle \overline{q} q \rangle \sim \Lambda^3_{\rm QCD}$ breaking chiral symmetry (and probably 4-quark condensates $\langle \overline{q} q \overline{q} q \rangle$ not reducible to $\langle \overline{q} q \rangle^2$)

Can six-quark condensates $\langle qqqqqq \rangle$ be formed? B violation
namely $\langle (udd)^2 \rangle$ or $\langle (uds)^2 \rangle$





Vafa-Witten theorem: QCD cannot break vector symmetries ...
.. but the prove relies on the absence of θ-term (i.e. valid for $\theta = 0$)
Imagine world $\theta \sim 1$ where $\langle qqqqqq \rangle \sim \Lambda^9_{\rm QCD}$ – bad for Life
– massless Goldstone β inducing $n \to \bar{n} + \beta$ transition in nuclei ...
Let us assume $\langle qqqqqq \rangle_\theta \sim F(\theta)\, \Lambda^9_{\rm QCD}$
$F(\theta)$ being smooth periodic even function: $F(\theta) = F(-\theta) = C\theta^2 + \ldots$
$\langle qqqqqq \rangle_\theta = C\theta^2 \Lambda^9_{\rm QCD} \sim C \times {\rm MeV}^9$ for $\theta \sim 10^{-10}$
– can such a fuzzy condensate be OK? Maybe in dense matter?

Summary

Puzzles are emerging related to the neutron decays
– If true, they may trace to new physics at TeV scale
(new measurements + accurate lattice simulations are needed ...)

- Cabibbo angle anomaly (neutron β-decay vs. Kaon decays)
- Neutron lifetime anomaly (trap vs. beam)

Despite apparent vicinity, the two puzzles are different ...
– Mechanisms that could settle Cabibbo angle anomaly
(vector-like quarks or flavor gauge bosons at the TeV scale, etc)
do not explain the trap/beam lifetime discrepancy
– it requires some additional channel of the neutron disappearance

Dark decay $n \to n' + X$ increasing the total decay width is disfavored

Dark oscillation $n - n'$ (enhanced in magnetic field + $n' \to p'e'\bar{\nu}'$) is OK
... can be excluded by the regeneration (shining thru the absorber)
experiment $n \to n' \to n$ at the ORNL

Search for baryon violation: $n - \bar{n}$ $(\Delta B = 2)$ or $n - n'$ $(\Delta B = 1)$
and related processes is an attractive business
(the key for the universe baryon asymmetry, portal to DM and more ...)