Neutron Lifetime Puzzle and $n - n'$ conversions

Pictures at the Exhibition

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NORDITA, Stockholm, 10-14 Dec. 2018

Contents

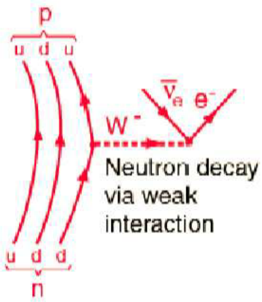
Promenade

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

Neutrons are stable in basic nuclei but decay in free state: $n \to pe\bar{\nu}_e$
... and in some (β^- unstable) nuclei
or can be even created in other (β^+ unstable) nuclei

$$\frac{G_F\,|V_{ud}|}{\sqrt{2}}\;\overline{u}(1-\gamma^5)\gamma^\mu d\;\;\overline{\nu}_e(1-\gamma^5)\gamma_\mu e$$

$$\frac{G_F\,|V_{ud}|}{\sqrt{2}}\;\overline{p}(1-g_A\gamma^5)\gamma^\mu n\;\;\overline{\nu}_e(1-\gamma^5)\gamma_\mu e$$



Fermi Theory of V-A form – Standard Model
conserving baryon number

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

The Gnome

The lifetime puzzle

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

IN BRIEF

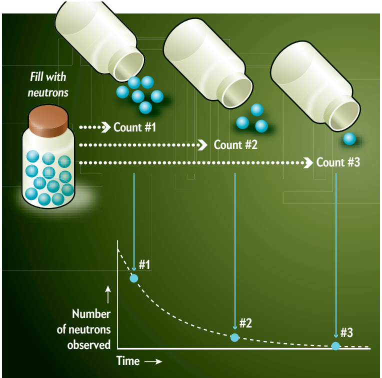
The best experiments in the world cannot agree on how long neutrons live before decaying into other particles.
Two main types of experiments are under way: bottle traps count the number of neutrons that survive after various intervals, and beam experiments look for the particles into which neutrons decay.
Resolving the discrepancy is vital to answering a number of fundamental questions about the universe.

Illustration by Bill Mayer

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.

Two methods to measure the neutron lifetime

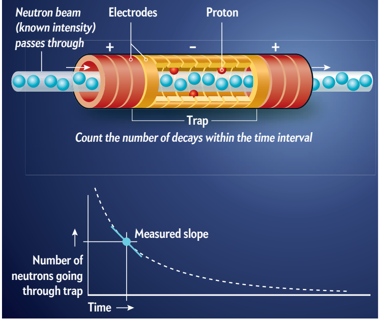


The Bottle Method

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.

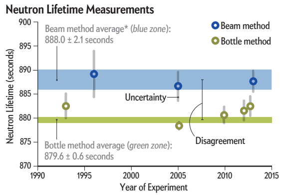
The Beam Method

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.



Problem ...

τ_n measured in two methods are different: $\tau_{\rm trap} < \tau_{\rm beam}$



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.

Can $n \to n'$ conversion be plausible explanation?
(by the way, what is $n - n'$ conversion ?)

Promenade *(2nd)*

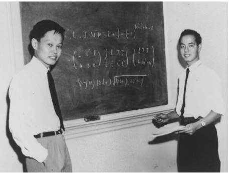
Alice @ Mirror World – *"Through the Looking-Glass" (1871)*

I'll tell you all my ideas about Looking-glass House. *The room you can see through the glass – that's just the same as our room … the books there are something like our books, only the words go the wrong way …* I see all of it – all but a bit just behind the fireplace. *I want so to know whether they've a fire*: you never can tell, unless *our fire smokes, and then smoke comes up in that room too …* Oh, how nice it would be if we could get through into Looking-glass House! Let's pretend there's a way of getting through into it, somehow … *It'll be easy enough to get through I declare!'*

Lewis Carroll

Parity Violation & Mirror Fermions – Lee and Yang, 1956

The conservation of parity is usually accepted without questions concerning its possible limit of validity being asked. The is actually no *a priori* reason why its violation is undesirable. Its violation implies the existence of right-left asymmetry and we have shown in the above some possible experimental tests os this asymmetry ...



If such asymmetry is indeed found, *the question could still be raised whether there could not exist corresponding elementary particles exhibiting opposite asymmetry such that in the broader sense there will still be over-all right-left symmetry. If this is the case, there must exist two kinds of protons p_R and p_L, the right-handed one and the left-handed one.* At the present time the protons in the laboratory must be predominantly of one kind to produce the supposedly observed asymmetry. *This means that the free oscillation period between them must be longer than the age of the Universe. They could therefore both be regarded as stable particles. The numbers of p_R and p_L must be separately conserved.* Both p_R and p_L could interact with the same E-M field and perhaps the same pion field ...

Mirror Fermions as parallel sector – *Kobzarev, Okun, Pomeranchuk, 1966*

In connection with the discovery of CP violation, we discuss the possibility that "mirror" (R) particles exist in addition to the ordinary (L) particles. The introduction of these particles reestablishes the equivalence of left and right. It is shown that *mirror particles cannot interact with ordinary particles strongly, semistrongly or electromagnetically. L and R particles must have the same gravitational interactions. The possibility of existence and detection of macroscopic bodies (stars) made up of R-matter is discussed.*

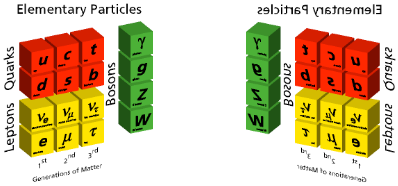
This papers were written before the Standard Model ...

The Old Castle

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

$$G \times G'$$

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 $\quad \mathcal{L}_{mix}$

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

Fermions and anti-fermions :

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

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

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

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

Twin Fermions and anti-fermions :

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

B′=1/3 L′=1 B′=1/3 L′=1

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

B′=-1/3 L′=-1 B′=-1/3 L′=-1

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

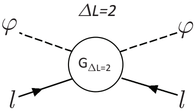
Doubling symmetry $(L, R \to L, R$ parity$)$: $\quad Y' = Y \qquad B - B' \to -(B - B')$

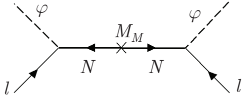
Mirror symmetry $(L, R \to R, L$ parity$)$: $\quad Y' = Y^* \qquad B - B' \to B - B'$

Promenade (3rd)

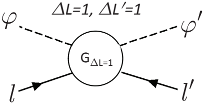
B-L violation in O and M sectors: active-sterile neutrinos

- $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$ $(\Delta L = 2)$ – neutrino (seesaw) masses $m_\nu \sim v^2/M$
M is the (seesaw) scale of new physics beyond EW scale.





- Neutrino -mirror neutrino mixing – (active - sterile mixing)
L and L' violation: $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$, $\frac{1}{M}(l'\bar{\phi}')(l'\bar{\phi}')$ and $\frac{1}{M}(l\bar{\phi})(l'\bar{\phi}')$

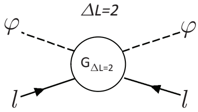


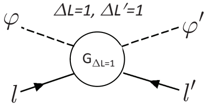
Mirror neutrinos are natural candidates for sterile neutrinos

Akhmedov, ZB, Senjanovic 92; ZB, Mohapatra 95

Co-baryogenesis: B-L violating interactions between O and M worlds

L and L' violating operators $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$ and $\frac{1}{M}(l\bar{\phi})(l'\bar{\phi}')$ lead to processes $l\phi \to \bar{l}\bar{\phi}$ $(\Delta L = 2)$ and $l\phi \to \bar{l}'\bar{\phi}'$ $(\Delta L = 1,\ \Delta L' = 1)$





After inflation, our world is heated and mirror world is empty: but ordinary particle scatterings transform them into mirror particles, heating also mirror world.

- These processes should be out-of-equilibrium
- Violate baryon numbers in both worlds, $B - L$ and $B' - L'$
- Violate also CP, given complex couplings

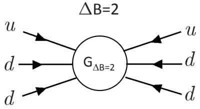
- Green light to celebrated conditions of Sakharov
  can explain $\Omega'_B/\Omega_B \simeq 5$ *Bento and ZB, 2001; ZB 2003*

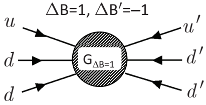
B violating operators between O and M particles in $\mathcal{L}_{\rm mix}$

Ordinary quarks $u, \; d$ (antiquarks $\bar{u}, \; \bar{d}$)
Mirror quarks $u', \; d'$ (antiquarks $\bar{u}', \; \bar{d}'$)

- Neutron -mirror neutron mixing – (active - sterile neutrons)

$$\frac{1}{M^5}(udd)(udd) \text{ and } \frac{1}{M^5}(udd)(u'd'd') \quad (+ \text{ h.c.})$$



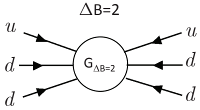


Oscillations $n(udd) \leftrightarrow \bar{n}(\bar{u}\bar{d}\bar{d}) \quad (\Delta B = 2)$
$n(udd) \to \bar{n}'(\bar{u}'\bar{d}'\bar{d}'), \; n'(udd) \to \bar{n}(\bar{u}\bar{d}\bar{d}) \quad (\Delta B = 1, \; \Delta B' = -1)$

can co-generate Baryon asymmetries in both worlds with $\Omega'_B \simeq 5\,\Omega_B$

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 $n(udd) \to \bar{n}(\bar{u}\bar{d}\bar{d})$, with oscillation time $\tau = \epsilon^{-1}$

$$\varepsilon = \langle n|(udd)(udd)|\bar{n}\rangle \sim \frac{\Lambda^6_{\rm QCD}}{M^5} \sim \left(\frac{100\ \rm TeV}{M}\right)^5 \times 10^{-25}\ \rm eV$$

Key moment: *$n - \bar{n}$ oscillation destabilizes nuclei:*
$(A, Z) \to (A-1, \bar{n}, Z) \to (A-2, Z/Z-1) + \pi$'s

Present bounds on ϵ from nuclear stability

$\varepsilon < 1.2 \times 10^{-24}$ eV	$\to$	$\tau > 1.3 \times 10^8$ s	Fe, Soudan 2002
$\varepsilon < 2.5 \times 10^{-24}$ eV	$\to$	$\tau > 2.7 \times 10^8$ s	O, SK 2015

Free neutron– antineutron oscillation

Two states, n and $\bar{n}$

$$H = \begin{pmatrix} m_n + \mu_n \mathbf{B}\sigma & \varepsilon \\ \varepsilon & m_n - \mu_n \mathbf{B}\sigma \end{pmatrix}$$

Oscillation probability $P_{n\bar{n}}(t) = \frac{\varepsilon^2}{\omega_B^2} \sin^2(\omega_B t)$, $\omega_B = \mu_n B$

If $\omega_B t \gg 1$, then $P_{n\bar{n}}(t) = \frac{1}{2}(\varepsilon/\omega_B)^2 = \frac{(\varepsilon t)^2}{(\omega_B t)^2}$

If $\omega_B t < 1$, then $P_{n\bar{n}}(t) = (t/\tau)^2 = (\varepsilon t)^2$

"Quasi-free" regime: for a given free flight time t, magnetic field should be properly suppressed to achieve $\omega_B t < 1$.

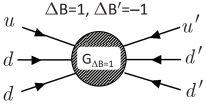
More suppression makes no sense !

Exp. Baldo-Ceolin et al, 1994 (ILL, Grenoble) :
$\tau > 0.9 \times 10^8$ s $\rightarrow$ $\varepsilon < 7.7 \times 10^{-24}$ eV

At ESS 2 orders of magn. better sensitivity can be achieved, $\varepsilon \sim 10^{-25}$ eV

Neutron – mirror neutron mixing

Effective operator $\frac{1}{M^5}(udd)(u'd'd') \quad \rightarrow \quad$ 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:*
$(A,Z) \rightarrow (A-1,Z) + n'(p'e'\bar{\nu}')$ 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 $n \rightarrow \bar{n}'$ and regeneration $n \rightarrow \bar{n}' \rightarrow n$

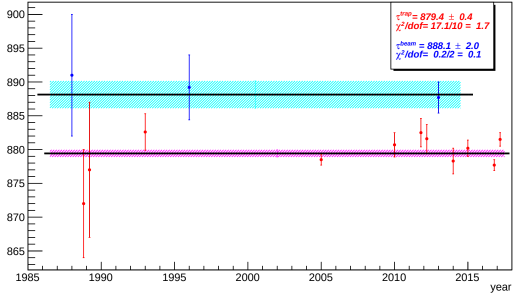
Tuileries *(Children's Quarrel after Games)*

Discrepancy between trap and beam methods

Beam method measures neutron β-decay ($n \to pe\bar{\nu}_e$) width $\Gamma_\beta = \tau_\beta^{-1}$

Trap method measures neutron total decay width $\Gamma_n = \tau_n^{-1}$

Standard Model (and common wisdom of baryon conservation) tell that both should be the same, $\Gamma_n = \Gamma_\beta$ But ...



$\tau_{\rm trap} = 879.4 \pm 0.5$ s $\qquad \tau_{\rm beam} = 888.0 \pm 2.0$ s

$\Delta\tau = \tau_{\rm beam} - \tau_{\rm trap} = (8.6 \pm 2.1)$ s $\qquad$ more than 4σ discrepancy

The Neutron Dark Decay

If this discrepancy is real (not due to some yet unknown systematics)

then New Physics should be invoked which could consistently explain the relations between the neutron decay width Γ_n, β-decay rate Γ_β, and the measured values $\tau_{\rm trap}$ and $\tau_{\rm beam}$

Some time ago I proposed a way out assuming that the neutron has a new decay channel $n \to n'X$ into a 'dark neutron' n' and light bosons X among which a photon, due to a mass gap $m_n - m_{n'} \simeq 1$ MeV. Then $\Gamma_\beta = \tau_{\rm beam}^{-1}$ and $\Gamma_n = \Gamma_\beta + \Gamma_{\rm new} = \tau_{\rm trap}^{-1}$,

$\tau_{\rm trap}/\tau_{\rm beam}$ discrepancy could be explained by a branching ratio $\mathrm{Br}(n \to n'X) = \Gamma_{\rm new}/\Gamma_n \simeq 0.01$.

$n - n'$ transitional magnetic moment

$n - n'$ mass mixing $\epsilon\, nCn' + \mathrm{h.c.}$

and transitional magnetic (electric) dipole moments

$\mu_{nn'}(F_{\mu\nu} + F'_{\mu\nu})nC\sigma^{\mu\nu}n' + \mathrm{h.c.}$

Hamiltonian of n and n' system becomes

$$H = \begin{pmatrix} m_n + \mu_n \mathbf{B}\sigma & \epsilon + x\mu_n(\mathbf{B} + \mathbf{B}')\sigma \\ \epsilon + x\mu_n(\mathbf{B} + \mathbf{B}')\sigma & m'_n + \mu_n \mathbf{B}'\sigma \end{pmatrix}, \quad x = \frac{\mu_{nn'}}{\mu_n}$$

Interplay of ϵ and $\mu_{nn'}$ can alleviate problem ....

Toccata: invisible decay

Imagine that mirror parity is not perfect,
but it is mildly broken (e.g. by some parity odd scalar)

So that particle masses in O and M sectors have tiny differences:

$m_n > m'_n$, $m_n - m'_n = \Delta m \leq 1$ MeV, and $|m'_p - m'_n| \simeq MeV$

Now free neutron can decay in invisible mode $n \to n' + \eta$, where η can be some massless boson. E.g. it can be Goldstone if mass mixing term $\beta n C n' + \mathrm{h.c.}$ emerges via spontaneous breaking of $U(1)_B \times U(1)'_B$ by some Higgs $\chi(1,1)$.

Trap method – the neutron total width: $\tau_{\rm dec}^{-1} = \Gamma_{\rm tot} = \Gamma_{\rm vis} + \Gamma_{\rm inv}$

beam method – β-decay width $\Gamma_{\rm vis}(n \to pe\bar{\nu}) = \tau_{\rm beam}^{-1} \simeq 10^{-27}$ GeV.

$\Gamma_{\rm inv}(n \to n'\eta) \simeq 10^{-29}$ will suffice for 1 % discrepancy ...

If $m'_p > m_n > m_p > m'_n$, n' can be self-interacting DM $(\sigma/m \sim 1b/\mathrm{GeV})$

... and Fuga: not so invisible decay via $\mu_{nn'}$

Decay via transitional magnetic moment

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

Branching $\mathrm{Br}(n'\gamma) \simeq 10^{-2}$ can be obtained then for $\Delta m \simeq 1$ MeV and $x = \mu_{nn'}/\mu_n \sim 10^{-9}$

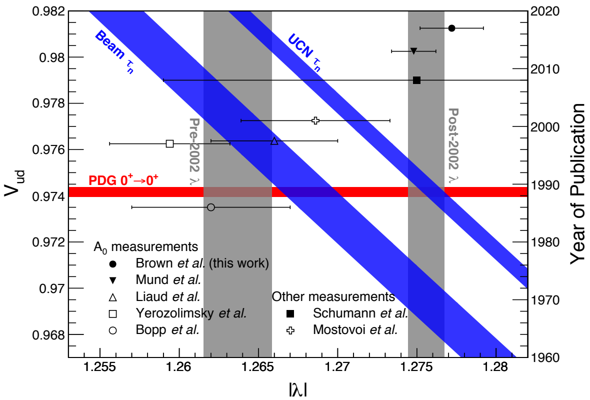
Imagine what incredible consequences for Neutron Star transformations ....

To be Continued ..... Stay Tuned !

These were slides of my talk
"Unusual effects in $n - n'$ conversion"
at INT Workshop INT-17-69W, Seattle, 23-27 Oct. 2017,

http://www.int.washington.edu/talks/WorkShops/int-17-69W/People/Berezhiani-Z/Berezhiani3.pdf

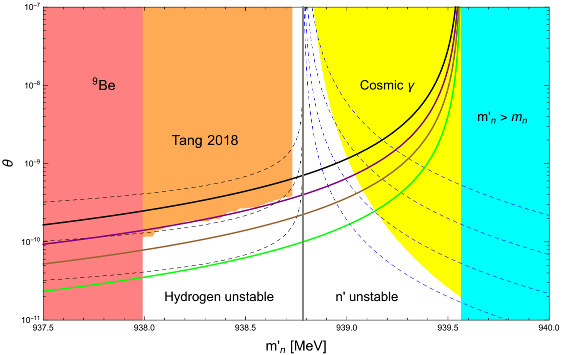
Problem: τ_n vs. superallowed $0^+ - 0^+$ and β-asymmetry



Brown et al, *et al.*, arXiv:1712.00884

Can BSM physics help? new contribution to β decay $n \to pe\bar{\nu}_e$,
E.g. scalar formfactor mediated by charged scalar (extra Higgs doublet) – Cannot not help!

Implications of the Neutron Dark Decay



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

$\mathrm{Br}(n \to n'\gamma) = 0.001, \mathrm{Br}(n \to n'\gamma') = 0.009$

$m_{n'} > m_p + m_e$, DM decays $n' \to pe\bar{\nu}_e$ $(\tau = 10^{14}, 10^{15}, 10^{16}, 10^{17}$ yr)

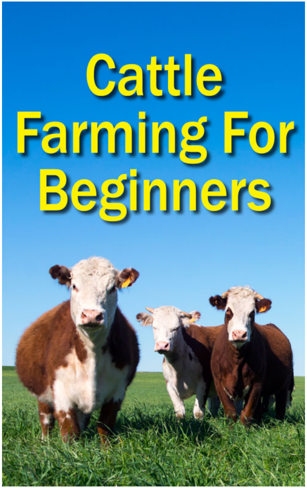
$m_{n'} < m_p + m_e$, Hydrogen atom decays $pe \to n'\nu_e$ $(\tau = 10^{20}, 10^{21}, 10^{22}$ yr)

Hydrogen Lifetime ?

There is more stupidity than hydrogen in the universe, and it has a longer lifetime. – Frank Zappa

Two things are infinite: the universe and human stupidity; but I'm not sure about the universe. – Albert Einstein

Cattle



... Curiosity

Evidently, some people stayed tuned .... after couple of months

Fornal and Grinstein, "Dark Matter Interpretation of the Neutron Decay Anomaly," arXiv:1801.01124
– all as in above but $n' \to \chi$ becomes elementary particle

followed by a train of publications

Tang *et al.*, "Search for the Neutron Decay n$\to$ X$+\gamma$ where X is a dark matter particle," arXiv:1802.01595 – no such decay observed

Czarnecki, Marciano, Sirlin, "The Neutron Lifetime and Axial Coupling Connection," arXiv:1802.01804 – tension with measured asymmetries

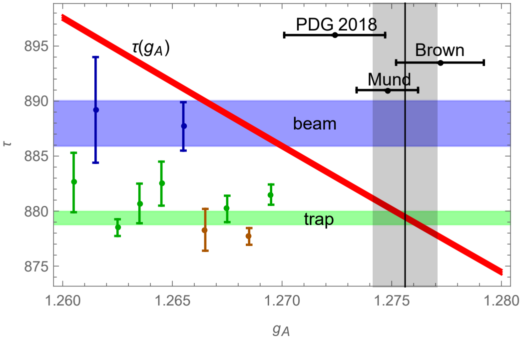
Serebrov *et al.*, "Neutron lifetime, dark matter and search for sterile neutrino," arXiv:1802.06277 – chain reactions and reactor neutrinos

McKeen, Nelson, Reddy, Zhou, "Neutron stars exclude light dark baryons", arXiv:1802.08244 – no NS could exist ...

R.I.P

Ballet of Unhatched Chicks

τ_n vs. β-asymmetry



$$\tau_\beta(1+3g_A^2) = (5172.0 \pm 1.1)\ \mathrm{s}$$ Czarnecki, Marciano, Sirlin, 18

$$g_A = 1.2755 \pm 0.0011 \quad \longrightarrow \quad \tau_\beta^{\mathrm{SM}} = 879.5 \pm 1.3\ \mathrm{s}$$

$$\tau_{\mathrm{beam}} = 888.0 \pm 2.0\ \mathrm{s} \qquad \tau_{\mathrm{trap}} = 879.4 \pm 0.5\ \mathrm{s}$$

So experimentally we have $\tau_{\mathrm{trap}} = \tau_n = \tau_\beta < \tau_{\mathrm{beam}}$

while dark decay predicts $\tau_{\mathrm{trap}} = \tau_n < \tau_\beta = \tau_{\mathrm{beam}}$ Not Good!

Samuel Goldenberg and Schmuile

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Constraints on mirror models of dark matter from observable neutron-mirror neutron oscillation

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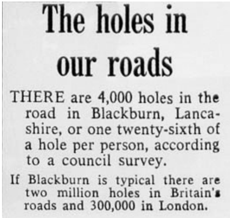
ABSTRACT

The process of neutron-mirror neutron oscillation, motivated by symmetric mirror dark matter models, is governed by two parameters: $n - n'$ mixing parameter δ and $n - n'$ mass splitting Δ. For neutron mirror neutron oscillation to be observable, the splitting between their masses Δ must be small and current experiments lead to $\delta \le 2 \times 10^{-27}$ GeV and $\Delta \le 10^{-24}$ GeV. We show that in mirror universe models where this process is observable, this small mass splitting constrains the way that one must implement asymmetric inflation to satisfy the limits of Big Bang Nucleosynthesis on the number of effective light degrees of freedom. In particular we find that if asymmetric inflation is implemented by inflaton decay to color or electroweak charged particles, the oscillation is unobservable. Also if one uses SM singlet fields for this purpose, they must be weakly coupled to the SM fields.

$$n - n' \text{ mass difference} \quad \Delta m = m'_n - m_n \neq 0$$

Limoges. The Market (The Great News)



The holes in our roads

THERE are 4,000 holes in the road in Blackburn, Lancashire, or one twenty-sixth of a hole per person, according to a council survey.

If Blackburn is typical there are two million holes in Britain's roads and 300,000 in London.

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

Consider $n - n'$ system with $\Delta m = m'_n - m_n \sim 10^{-7}$ eV
and $\epsilon \sim (1\,\mathrm{TeV}/M)^5 \times 10^{-10}$ eV

Hamiltonian of (n_+, n_-, n'_+, n'_-) system ($\pm$ for 2 spin states)

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

where $\Omega_B = |\mu_n B| = (B/1\,\mathrm{T}) \times 60$ 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 $P_{nn'} \approx \theta_0^2 \sim 10^{-6}$.

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

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 accurately estimate the UCN loss rates and subtract them:
$\tau_n^{-1} = \Gamma_{\rm st} - \Gamma_{\rm loss}; \quad \Gamma_{\rm loss} = \langle P_{\rm loss} f_{\rm wall} \rangle$.

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 more lifetimes.

So, to please Anatoly, I take $P_{nn'} = \theta_0^2 \leq 10^{-6}$ ....

Average of material trap experiments: $\tau_{\rm mat} = 880.2 \pm 0.5$ s,

where the UCN $n \to n'$ losses are already 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:
$\tau_n^{-1} = \Gamma_{\rm st} - \Gamma_{\rm loss}$;

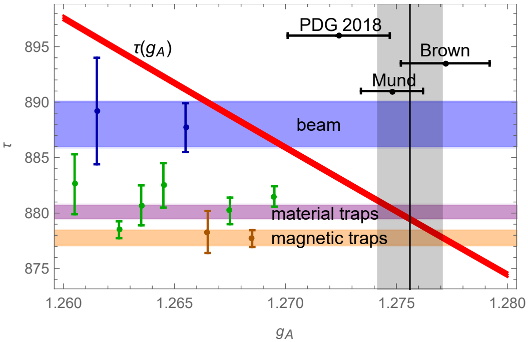
The UCN losses are estimated to be almost irrelevant: about 0.2 s correction But losses per scattering are not measured and only depolarisation rate is controlled:
On the other hand, $\Gamma_{\rm loss} = \langle f_{\rm scat} P_{nn'} \rangle$ with $P_{nn'} \sim 10^{-6}$ would give $1 \div 2$ s correction.

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 ...

τ_n vs. β-asymmetry: $\tau_\beta(1+3g_A^2) = (5172.0 \pm 1.1)$ s



$g_A = 1.2755 \pm 0.0011 \quad \longrightarrow \quad \tau_\beta^{\rm SM} = 879.5 \pm 1.3$ s

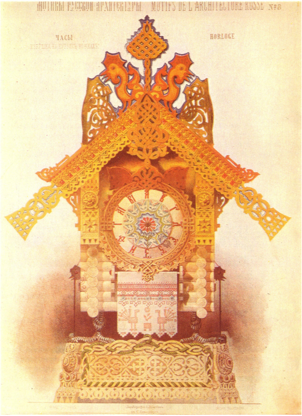
$\tau_{\rm beam} = 888.0 \pm 2.0$ s $\qquad \tau_{\rm trap} = 879.4 \pm 0.5$ s

$\tau_{\rm mat} = 880.2 \pm 0.5$ s, $\quad \tau_{\rm magn} = 877.8 \pm 0.7$ s (2.6σ discrepancy)

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

what s exactly predicted in my scenario $\quad$ So far so Good!

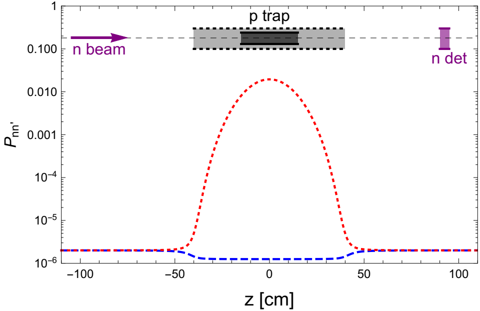
The Hut on Hen's Legs (Baba Yaga)



Beam Experiments

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

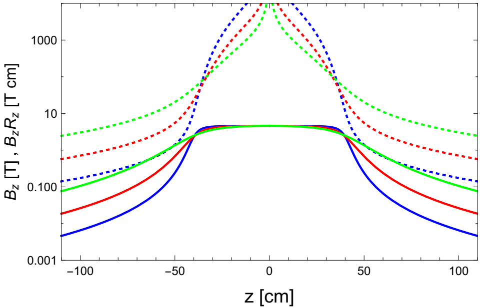
$N_n = P^{\rm tr}_{nn} L \int_A da \int dv\, I(v)/v$ and $N_{n'} = P^{\rm tr}_{nn'} L \int_A da \int dv\, I(v)/v$



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

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

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



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

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

* * * * * *

Neutron Lifetime Puzzle and $n - n'$ conversions

Pictures at the Exhibition

Zurab Berezhiani

Catacombs (Roman Tomb)

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

The Bogatyr Gates

(In the Capital in Kiev)

Thank You ...

It's wonderful to be here
It's certainly a thrill
You're such a lovely audience
We'd love to take you home

I don't really want to stop the show
But I thought that you might like to know
That the singer's going to sing a song
And he wants you all to sing along

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