Neutron–Mirror Neutron Mixing: (*fantastique*) astrophysical consequences

Symphonie en cinq parties: Épisode de la vie d'un artiste

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Contents

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Quick overview of Symphony ...

Parallel/mirror sector of particles as a duplicate of our SM: $SM \times SM'$ (or $SU(5) \times SU(5)'$ or $E_8 \times E_8'$ or parallel branes ... or more sectors)
– all our particles (e, p, n, ν, γ...) have dark M twins (e', p', n', ν', γ'...) of exactly (or almost) the same masses

M matter is viable DM (asymmetric/baryonic/atomic/self-interacting/dissipative etc. as ordinary (O) baryon matter) – but M sector must be colder than O sector: $T'/T < 0.2$ or so (BBN, CMB, LSS etc.)
– asymmetric reheating between the two sectors after inflation

– O matter mainly hydrogen (H 75%, ^{4}He 25%)
while M matter mostly helium (H$'$ 25%, ^{4}He$'$ 75%) – first M stars are formed earlier than O stars, are bigger, helium dominated and end up in heavy BH: $M \sim (10 \div 10^2)\, M_\odot$ (inferring $\sim 80\%$ of DM in galactic halo and for the rest of $\sim 20\%$ – M gas clouds, $\sim M_\odot$ stars etc.

There can exist interactions between O and M particles, e.g. photon kinetic mixing $\varepsilon F^{\mu\nu} F'_{\mu\nu}$, some common gauge bosons, etc.
Most interesting are the ones which violate baryon and lepton numbers between two sectors, and namely $B - L$ and $B' - L'$ which can co-generate baryon asymmetries in both sectors – and naturelly explain why the DM and baryon fractions are comparable, $\Omega_{B'}/\Omega_B \simeq 5$ or so

... Quick overview of Symphony

These interactions can induce mixing of neutral particles between two sectors, e.g. $\nu - \nu'$ oscillations (M neutrinos = sterile neutrinos)

Oscillation $n \to n'$ can be very effective process, faster than the neutron decay. For certain parameters it can explain the neutron lifetime problem, 4.5σ discrepancy between the decay times measured by different experimental methods (bottle and beam), or anomalous neutron loses observed in some experiments and paradoxes in the UHECR detections

$n \to n'$ transition can have observable effects on neutron stars. It creates dark cores of M matter in the NS interiors, or eventually can transform them into maximally mixed stars with equal amounts of O and M neutrons

Such transitions in mirror NS create O matter cores. If baryon asymmetry in M sector has opposite sign, transitions $\bar{n}' \to \bar{n}$ create antimatter cores which can be seen by LAT (talk by Von Balmoos) and explain the origin of mirror nuclei in cosmic rays seen by AMS2 (talk by Salati)

If neutron has mixings both with M neutron and M antineutron, then the neutron can be promptly transformed into the antineutron via travelling in M world, $n \to n'/\bar{n}' \to \bar{n}$. This can be tested in oscillation experiments with magnetic fields. If discovered, the cheap and ecologically clean machines become possible producing energy (almost) for free

Movement I – *canto espressivo*

Rêveries – Passions

Dreams – Passions

Artist in his dreams sees a charming woman and falls in desperate love with her. The beloved image appears in his visions in association with a sensual musical leitmotiv ...

Visible vs. Dark matter: $\Omega_D/\Omega_B \sim 1$?

Visible matter from Baryogenesis

B ($B-L$) & CP violation, Out-of-Equilibrium

$\rho_B = n_B m_B$, $m_B \simeq 1$ GeV, $\eta = n_B/n_\gamma \sim 10^{-9}$

η is model dependent on several factors:

coupling constants and CP-phases, particle degrees of freedom, mass scales and out-of-equilibrium conditions, etc.

- Sakharov 1967

Dark matter: $\rho_D = n_X m_X$, but $m_X = ?$, $n_X = ?$

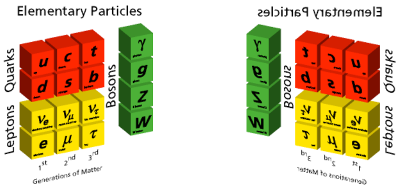
n_X is model dependent: DM particle mass and interaction strength (production and annihilation cross sections), freezing conditions, etc.

- Axion — $m_a \sim 10^{-5}$ eV $n_a \sim 10^4 n_\gamma$ - CDM
- Neutrinos — $m_\nu \sim 10^{-1}$ eV $n_\nu \sim n_\gamma$ - HDM $(\times)$
- Sterile ν' — $m_{\nu'} \sim 10$ keV $n_{\nu'} \sim 10^{-3} n_\nu$ - WDM
- Mirror baryons — $m_{B'} \sim 1$ GeV $n_{B'} \sim n_B$ - ???
- WIMP — $m_X \sim 1$ TeV $n_X \sim 10^{-3} n_B$ - CDM
- WimpZilla — $m_X \sim 10^{14}$ GeV $n_X \sim 10^{-14} n_B$ - CDM

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

$G \times G'$

Regular world — Mirror world



- Two identical gauge factors, e.g. $SU(5) \times SU(5)'$, with identical field contents and Lagrangians: $\mathcal{L}_{\rm tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\rm mix}$
- Mirror sector ($\mathcal{L}'$) is dark – or perhaps grey? ($\mathcal{L}_{\rm mix} \to$ portals)
- MM is similar to standard matter, (asymmetric/dissipative/atomic) but realized in somewhat different cosmological conditions ($T'/T \ll 1$)
- $G \to G'$ symmetry (Z_2 or Z_2^{LR}): no new parameters in $\mathcal{L}'$ spont. broken?
- Cross-interactions between O & M particles

  $\mathcal{L}_{mix}$: new operators – new parameters! limited only by experiment!

$SU(3)\times SU(2)\times U(1)$ vs. $SU(3)'\times SU(2)'\times U(1)'$

Two possible parities: with and without chirality change

fermions and anti-fermions :

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

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

$\updownarrow$ CP

$$\bar q_R = \begin{pmatrix} \bar u_R \\ \bar d_R \end{pmatrix}, \quad \bar\ell_R = \begin{pmatrix} \bar\nu_R \\ \bar e_R \end{pmatrix}; \qquad \bar u_L,\ \bar d_L, \qquad \bar e_L$$

B=–1/3 L=–1 B=–1/3 L=–1

Mirror fermions and antifermions :

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

B′=1/3 L′=1 B′=1/3 L′=1

$\updownarrow$ CP

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

B′=-1/3 L′=-1 B′=-1/3 L′=-1

$$\mathcal{L}_{\rm Yuk} = F_L Y \bar F_L \phi \ + \ \text{h.c.} \qquad \mathcal{L}'_{\rm Yuk} = F'_L Y' \bar F'_L \phi' \ + \ \text{h.c.}$$

Z_2: $L(R) \leftrightarrow L'(R')$: $Y'_{u,d,e} = Y_{u,d,e}$ B,L $\leftrightarrow$ B′,L′

Z_2^{LR}: $L(R) \leftrightarrow R'(L')$: $Y'_{u,d,e} = Y^*_{u,d,e}$ B,L $\leftrightarrow$ −B′,L′ $Z_2^{LR} = Z_2\times$CP

– Sign of baryon asymmetries (BA)?

Ordinary BA is positive: $\mathcal{B} = \mathrm{sign}(n_b - n_{\bar{b}}) = 1$
– as produced by (unknown) baryogenesis a la Sakharov!

Sign of mirror BA, $\mathcal{B}' = \mathrm{sign}(n_{b'} - n_{\bar{b}'})$, is a priori unknown!

Imagine a baryogenesis mechanism *separately* acting in O and M sectors!
– without involving cross-interactions in $\mathcal{L}_{\rm mix}$
E.g. EW baryogenesis or leptogenesis $N \to \ell\phi$ and $N' \to \ell'\phi'$

Z_2: $\to Y'_{u,d,e} = Y_{u,d,e}$ i.e. $\mathcal{B}' = 1$
– O and M sectors are CP-identical in same chiral basis! O=left, M=left

Z_2^{LR}: $\to Y'_{u,d,e} = Y^*_{u,d,e}$ i.e. $\mathcal{B}' = -1$
– O sector in L-basis is identical to M sector in R-basis! O=left, M=right

In the absence of cross-interactions in $\mathcal{L}_{\rm mix}$ we cannot measure sign of BA (or chirality in weak interactions) in M sector – so all remains academic ...

But switching on cross-interactions, violating B and B′ – but conserving say B-B′ as neutron–mirror neutron mixing: $\epsilon n' n + \mathrm{h.c.}$
$\mathcal{B}' = -1 \quad \to \quad \bar{n}' \to n$ M (anti)matter → O matter
$\mathcal{B}' = 1 \quad \to \quad n' \to \bar{n}$ M matter → O antimatter

Movement II

Waltz in 3/8 – dolce e tenero

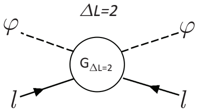
Un Bal

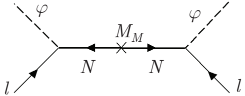
A Ball

The artist mind transports him to a fest party, in the quite nature of the countryside ... but the leitmotiv of the beloved image keeps tormenting him and throws into confusion and sensual excitement

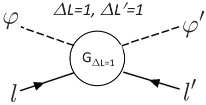
B-L violation in O and M sectors: Active-sterile mixing

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



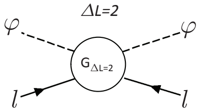


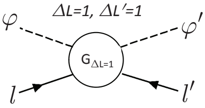
- Neutrino -mirror neutrino mixing – (active - sterile mixing)
L and L' violation: $\frac{A}{M}(\ell\phi)(\ell\phi)$, $\frac{A}{M}(\ell'\phi')(\ell'\phi')$ and $\frac{B}{M}(\ell\phi)(l\ell'\phi')$



Mirror neutrinos naturally sterile neutrinos: $\langle\phi'\rangle/\langle\phi\rangle \sim 10 \div 10^2$
ZB and Mohapatra 95, ZB, Dolgov and Mohapatra 96

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





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

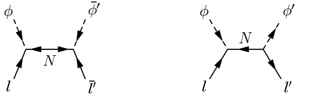
- These processes should be out-of-equilibrium
- Violate baryon numbers in both worlds, $B - L$ and $B' - L'$
- Violate also CP, given complex couplings

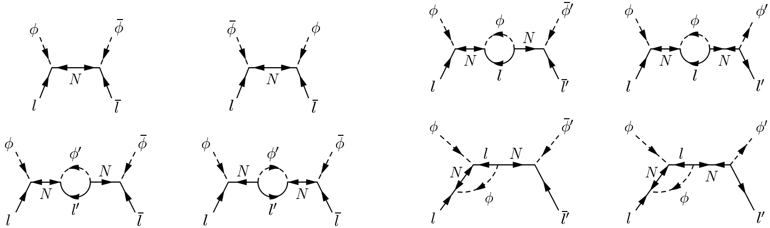
Green light to celebrated conditions of Sakharov

Co-leptogenesis:

Z.B. and Bento, PRL 87, 231304 (2001)

Operators $\frac{1}{M}(l\bar\phi)(l\bar\phi)$ and $\frac{1}{M}(l\bar\phi)(l'\bar\phi')$ via seesaw mechanism –
heavy RH neutrinos N_j with
Majorana masses $\frac{1}{2}Mg_{jk}N_jN_k + \mathrm{h.c.}$

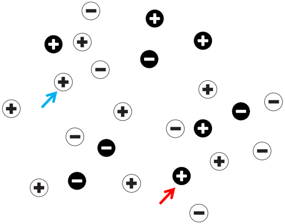




Complex Yukawa couplings $Y_{ij}l_iN_j\bar\phi + Y'_{ij}l'_iN_j\bar\phi' + \mathrm{h.c.}$

Z_2 (Xerox) symmetry $\rightarrow$ $Y' = Y$,
Z_2^{LR} (Mirror) symmetry $\rightarrow$ $Y' = Y^*$

Hot O World $\longrightarrow$ *Cold M World*



$$\frac{dn_{\rm BL}}{dt} + (3H+\Gamma)n_{\rm BL} = \Delta\sigma\, n_{\rm eq}^2$$

$$\frac{dn'_{\rm BL}}{dt} + (3H+\Gamma')n'_{\rm BL} = \Delta\sigma'\, n_{\rm eq}^2$$

$$\sigma(l\phi \to \bar l \bar\phi) - \sigma(\bar l\, \bar\phi \to l\phi) = \Delta\sigma$$

$$\sigma(l\phi \to \bar l'\bar\phi') - \sigma(\bar l\,\bar\phi \to l'\phi') = -(\Delta\sigma + \Delta\sigma')/2 \quad \to \quad 0 \quad (\Delta\sigma = 0)$$

$$\sigma(l\phi \to l'\phi') - \sigma(\bar l\,\bar\phi \to \bar l'\bar\phi') = -(\Delta\sigma - \Delta\sigma')/2 \quad \to \quad \Delta\sigma \quad (0)$$

$$\Delta\sigma = \mathrm{Im}\,\mathrm{Tr}[g^{-1}(Y^\dagger Y)^* g^{-1}(Y'^\dagger Y')g^{-2}(Y^\dagger Y)] \times T^2/M^4$$

$$\Delta\sigma' = \Delta\sigma(Y \to Y')$$

Mirror (Z_2^{LR}): $\quad Y' = Y^* \quad \to \quad \Delta\sigma' = -\Delta\sigma \quad \to \quad B > 0,\ B' > 0$

Xerox (Z_2): $\quad Y' = Y \quad \to \quad \Delta\sigma' = \Delta\sigma = 0 \quad \to \quad B, B' = 0$

If $k = \left(\frac{\Gamma}{H}\right)_{T=T_R} \ll 1$, neglecting Γ in eqs $\quad \to \quad n_{BL} = n'_{BL}$

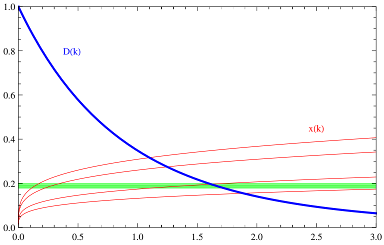
$$\Omega'_B = \Omega_B \simeq 10^3 \frac{J M_{Pl} T_R^3}{M^4} \simeq 10^3 J \left(\frac{T_R}{10^{11}\ \mathrm{GeV}}\right)^3 \left(\frac{10^{13}\ \mathrm{GeV}}{M}\right)^4$$

Cogenesis: $\Omega'_B \simeq 5\Omega_B$ Z.B. 2003

If $k = \left(\frac{\Gamma_2}{H}\right)_{T=T_R} \sim 1$, Boltzmann Eqs.

$$\frac{dn_{\rm BL}}{dt} + (3H+\Gamma)n_{\rm BL} = \Delta\sigma\, n_{\rm eq}^2 \qquad \frac{dn'_{\rm BL}}{dt} + (3H+\Gamma')n'_{\rm BL} = \Delta\sigma\, n_{\rm eq}^2$$

should be solved with Γ:



$D(k) = \Omega_B/\Omega'_B$, $x(k) = T'/T$ for different $g_*(T_R)$ and Γ_1/Γ_2.

So we obtain $\Omega'_B = 5\Omega_B$ when $m'_B = m_B$ but $n'_B = 5n_B$
– the reason: mirror world is colder

Movement III *Adagio in 6/8*

Scène aux champs ...

Scene in the country

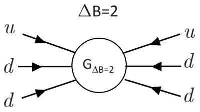
The artist is in countryside listening the wind gently blowing among the trees and two shepherds playing their horns .... he feels calm and happier and starts to hope that soon he will be with the beloved. Suddenly a distant sound of thunder explodes a thought: but what if she betrayed him?

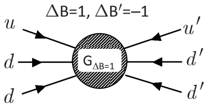
B violating operators between O and M particles in $\mathcal{L}_{\rm mix}$

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)

$$\frac{1}{M^5}(udd)(udd) \qquad \& \qquad \frac{1}{M^5}(udd)(u'd'd')$$

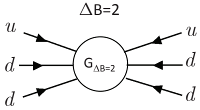




Oscillations $n \to \bar{n}$ $(\Delta B = 2)$
Oscillations $n \to \bar{n}'$ $(\Delta B = 1,\ \Delta B' = -1)$ $B + B'$ is conserved

Neutron– antineutron mixing

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 $\tau = \epsilon^{-1}$

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

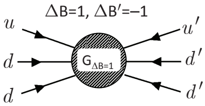
Key moment: *$n - \bar{n}$ oscillation destabilizes nuclei:* $(A, Z) \to (A-1, \bar{n}, Z) \to (A-2, Z/Z-1) + \pi$'s

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
$\varepsilon < 7.5 \times 10^{-24}$ eV	$\to$	$\tau > 0.9 \times 10^8$ s	direct limit free n

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 $B - B'$



$$\epsilon = \langle n|(udd)(u'd'd')|\bar{n}'\rangle \sim \frac{\Lambda^6_{\rm QCD}}{M^5} \sim \left(\frac{1 \ \mathrm{TeV}}{M}\right)^5 \times 10^{-10} \ \mathrm{eV}$$

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)

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

Neutron disappearance $n \to \bar{n}'$ and regeneration $n \to \bar{n}' \to n$
can be searched at small scale 'Table Top' experiments

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 ....

$n \to \bar{n}'$ or $n' \to \bar{n}$ conversions can be seen only with free neutrons.

Free neutrons are present only in

- Reactors and Spallation Facilities (experiments are looking for)
- In Cosmic Rays ($n - n'$ can reconcile TA and Auger experiments)
- During BBN epoch (fast $n' \to \bar{n}$ can solve Lithium problem)

– Transition $n \to \bar{n}'$ can take place for (gravitationally bound) Neutron Stars – conversion of NS into mixed ordinary/mirror NS

Neutron – mirror neutron oscillation probability

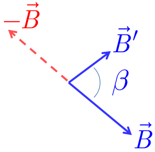
$$H = \begin{pmatrix} m + \mu\vec{B}\vec{\sigma} + V & \epsilon \\ \epsilon & m + \mu\vec{B}'\vec{\sigma} + V' \end{pmatrix}$$

The probability of n-n' transition depends on the relative orientation of magnetic and mirror-magnetic fields. The latter can exist if mirror matter is captured by the Earth

$$P_B(t) = p_B(t) + d_B(t) \cdot \cos\beta$$

$$p(t) = \frac{\sin^2\left[(\omega - \omega')t\right]}{2\tau^2(\omega - \omega')^2} + \frac{\sin^2\left[(\omega + \omega')t\right]}{2\tau^2(\omega + \omega')^2}$$

$$d(t) = \frac{\sin^2\left[(\omega - \omega')t\right]}{2\tau^2(\omega - \omega')^2} - \frac{\sin^2\left[(\omega + \omega')t\right]}{2\tau^2(\omega + \omega')^2}$$

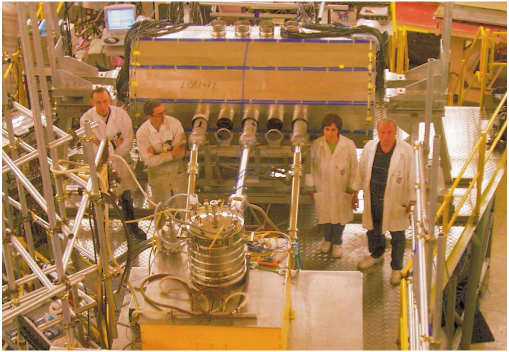


where $\omega = \frac{1}{2}|\mu B|$ and $\omega' = \frac{1}{2}|\mu B'|$; τ - oscillation time

$$A_B^{\det}(t) = \frac{N_{-B}(t) - N_B(t)}{N_{-B}(t) + N_B(t)} = N_{collis}\, d_B(t) \cdot \cos\beta \leftarrow \text{ assymetry}$$

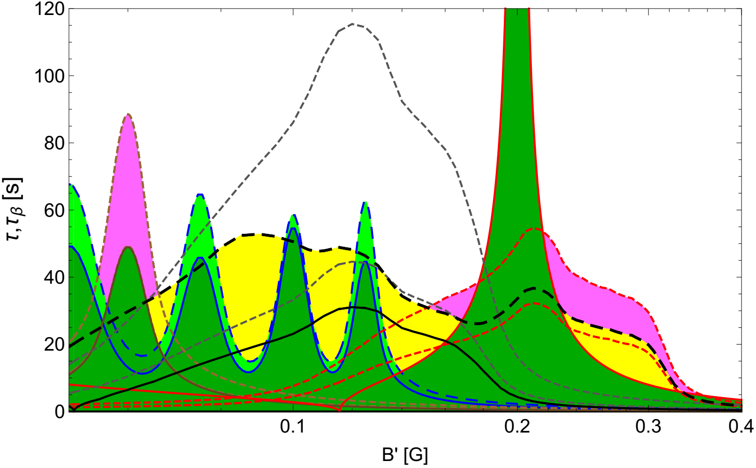
Experiments

By now 8 experiments were done at ILL/PSI (one exp by myself +collaborators using the UCN Chamber of 200 ℓ volume)



Several new experiments are underway at PSI, ILL and ORNL and are projected at ESS

Exp. limits on $n - n'$ oscillation time – ZB et al, Eur. Phys. J. C. 2018



Movement IV

Marche au supplice ...

March to the scaffold ...

Convinced that his love is unhappy, the artist poisons himself with opium which throws him into a heavy sleep accompanied by visions that he has killed his beloved, that he is condemned, led to the scaffold in a solemn procession, and he is witnessing his own execution ... Leitmotiv of the beloved appears as the final blow

Neutron Stars: $n - n'$ conversion

Two states, n and n'

$$H = \begin{pmatrix} m_n + V_n + \mu_n \vec{B}\vec{\sigma} & \varepsilon \\ \varepsilon & m'_n + V'_n - \mu_n \vec{B}'\vec{\sigma} \end{pmatrix}$$

$n_1 = \cos\theta n + \sin\theta n'$, $\quad n_2 = \sin\theta n - \cos\theta n'$, $\quad \theta \simeq \frac{\epsilon}{V_n - V'_n}$

Fermi degenerate neutron liquid $p_F \simeq (n_b/0.3\,\mathrm{fm}^{-3})^{2/3} \times 400$ MeV

$nn \to nn'$ with rate $\Gamma = 2\theta^2 \eta \langle \sigma v \rangle n_b$

$\frac{dN}{dt} = -\Gamma N \quad \frac{dN'}{dt} = \Gamma N \qquad N + N' = N_0$ remains Const.

$\tau_\epsilon = \Gamma^{-1} = \epsilon_{15}^{-2} \left(\frac{M}{1.5\, M_\odot} \right)^{2/3} \times 10^{15}$ yr $\quad N'/N_0 = t/\tau_\epsilon$

for $t = 10$ Gyr, $\tau_\epsilon = 10^{15}$ yr gives M fraction 10^{-5} – few Earth mass

$\dot{\mathcal{E}} = \frac{E_F N}{\tau_\epsilon} = \left(\frac{10^{15}\,\mathrm{yr}}{\tau_\epsilon} \right) \left(\frac{M}{1.5\, M_\odot} \right) \times 10^{31}$ erg/s $\quad$ NS heating – surface T

Mixed Neutron Stars: TOV and $M - R$ relations

$$g_{\mu\nu} = \mathrm{diag}(-g_{tt}, g_{rr}, r^2, r^2 \sin^2\theta) \qquad g_{tt} = e^{2\phi},\ g_{rr} = \frac{1}{1-2m/r}$$

$$T_{\mu\nu} = T^1_{\mu\nu} + T^2_{\mu\nu} = \mathrm{diag}(\rho g_{tt}, p g_{rr}, pr^2, pr^2\sin^2\theta)$$

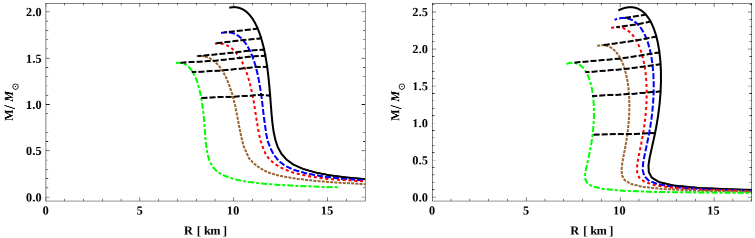
$$\rho = \rho_1 + \rho_2 \ \&\ p = p_1 + p_2, \qquad p_\alpha = F(\rho_\alpha)$$

$$\frac{dm}{dr} = 4\pi r^2 \rho \ \rightarrow\ \frac{dm_{1,2}}{dr} = 4\pi r^2 \rho_{1,2} \qquad m = m_1 + m_2$$

$$\frac{d\phi}{dr} = -\frac{1}{\rho+p}\frac{dp}{dr} \ \rightarrow\ \frac{dp_1/dr}{\rho_1+p_1} = \frac{dp_2/dr}{\rho_2+p_2}$$

$$\frac{dp}{dr} = (\rho+p)\frac{m+4\pi pr^3}{2mr-r^2}$$

$$(m_1 \neq 0, m_2 = 0)_{\rm in} \rightarrow (m_1 = m_2)_{\rm fin} \qquad r \rightarrow \frac{r}{\sqrt{2}}, \quad m_\alpha \rightarrow \frac{m_\alpha}{2\sqrt{2}}$$

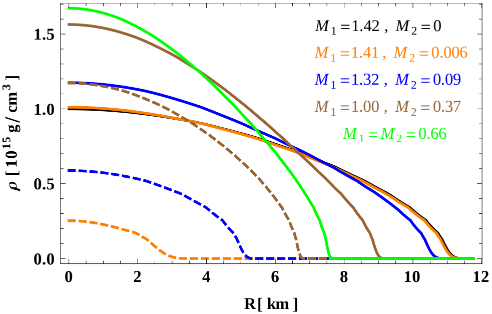


$$\sqrt{2}\ \text{rule:} \qquad M^{\rm max}_{\rm mix} = \frac{1}{\sqrt{2}} M^{\rm max}_{\rm NS} \qquad R_{\rm mix}(M) = \frac{1}{\sqrt{2}} R_{\rm NS}(M)$$

Neutron Star transformation

$\frac{dN}{dt} = -\Gamma N \quad \frac{dN'}{dt} = \Gamma \qquad N + N' = N_0$ remains Const.

Initial state $N = N_0,\ N' = 0$ final state $N = N' = \frac{1}{2} N_0$



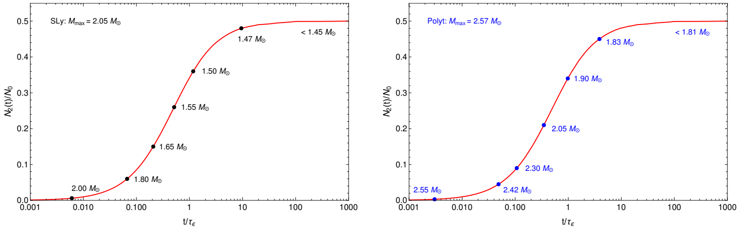
Quark stars: in strange quark matter (color-superconducting phase) transition is not energetically farored. So Quark stars (which perhaps are heavy pulsars with $M \simeq 2\,M_\odot$ or so) are insensitive to $n \to n'$.

Neutron Stars Evolution to mixed star

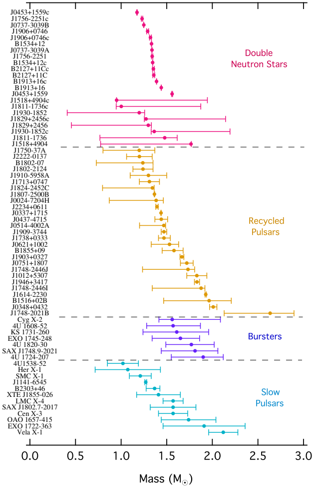
$\tau_\epsilon = (10^{-15}\,\mathrm{eV}/\epsilon)^2 \times 10^{15}$ yr   Two regimes are allowed :

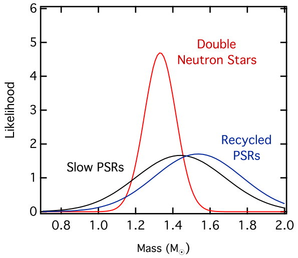
1. slow transformation ($\tau_\varepsilon \gg 14$ Gyr age of universe)
then limit from pulsar heating tells $\tau_\epsilon > 10^{15}$ yr $\longrightarrow$ $\epsilon < 10^{-15}$ eV or so
matches exp. limits for exactly degenerate $n - n'$

2. fast transformation $\tau_\epsilon < 10^5$ yr or so $\longrightarrow$ $\epsilon > 10^{-10}$ eV or so
– then old pulsars all should be transformed into maximally mixed stars
matches explanation of neutron lifetime anomaly, non-degenerate $n - n'$



Neutron Stars: mass distribution





Neutron Stars: observational $M - R$

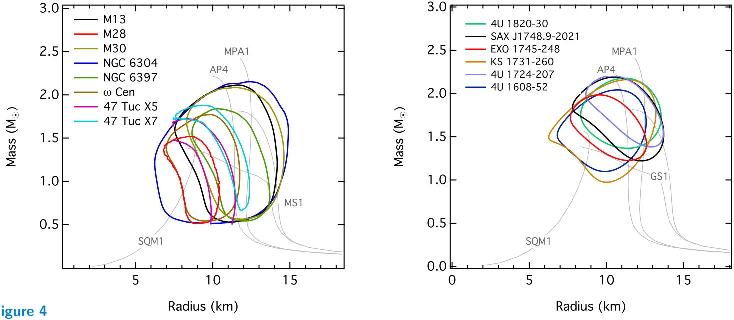


Figure 4

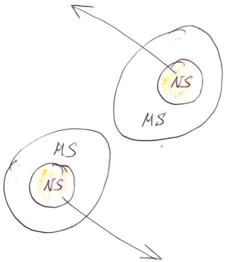
The combined constraints at the 68% confidence level over the neutron star mass and radius obtained from (Left) all neutron stars in low-mass X-ray binaries during quiescence (Right) all neutron stars with thermonuclear bursts. The light grey lines show mass-relations corresponding to a few representative equations of state (see Section 4.1 and Fig. 7 for detailed descriptions.)

Neutron Star Mergers

NS-NS merger and kilonova (GW170817 ?)
r-processes can give heavy *trans-Iron* elements

Mirror NS-NS merger is invisible (GW190425 ? $M_{\rm tot} = 3.4 M_\odot$)

But not completely ... if during the evolution they developed small core of our antimatter (depends on the mirror BA sign)
– their mergers can be origin of antinuclei for AMS-2



Antimatter Cores in Mirror Neutron stars

Neutron–Mirror Neutron Mixing: (*fantastique*) astrophysical consequences

Symphonie en cinq parties: Épisode de la vie d'un artiste

Zurab Berezhiani

Summary

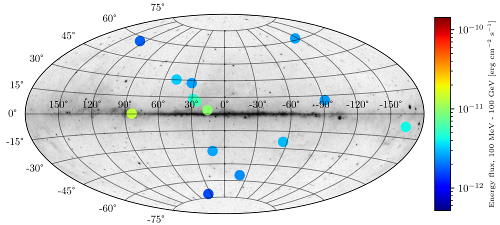


FIG. 1. Positions and energy flux in the 100 MeV–100 GeV range of antistar candidates selected in 4FGL-DR2. Galactic coordinates. The background image shows the *Fermi* 5-year all-sky photon counts above 1 GeV (image credit: NASA/DOE/Fermi LAT Collaboration).

Antimatter production rate: $\dot{N}_{\bar b} = \frac{N_0}{\tau_\epsilon} \simeq \epsilon_{15}^2 \left(\frac{M}{M_\odot}\right)^{2/3} \times 3\cdot 10^{34}\ \mathrm{s}^{-1}$

ISM accretion rate: $\dot{N}_b \simeq \frac{(2GM)^2 n_{\rm is}}{v^3} \simeq \frac{10^{32}}{v_{100}^3} \times \left(\frac{n_{\rm is}}{1/\mathrm{cm}^3}\right)\left(\frac{M}{M_\odot}\right)^2 \mathrm{s}^{-1}$

Annihilation γ-flux from the mirror NS as seen at the Earth:

$J \simeq \frac{10^{-12}}{v_{100}^3}\left(\frac{n_{\rm is}}{1/\mathrm{cm}^3}\right)\left(\frac{M}{1.5\,M_\odot}\right)^2\left(\frac{50\ \mathrm{pc}}{d}\right)^2 \frac{\mathrm{erg}}{\mathrm{cm}^2\mathrm{s}}$ d – distance to source

Alternative: Antistars – Dolgov & Co. but some difference:

– the surface redshift s expected $\sim 15 \div 30$ % for the NS

– which should be absent for antistars (weak gravity)

Getting Energy from Dark Parallel World

I argued that in O and M worlds baryon asymmetries can have same signs: $B > 0$ and $B' > 0$. Since $B - B'$ is conserved, our neutrons have transition $n \to \bar{n}'$ (which is the antiparticle for M observer)
while n' (of M matter) oscillates $n' \to \bar{n}$ into our antineutron

Neutrons can be transformed into antineutrons, but (happily) with low efficiency: $\tau_{n\bar{n}} > 10^8$ s

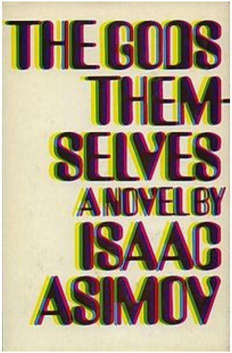
dark neutrons, before they decay, can be effectively transformed into our antineutrons in controllable way, by tuning vacuum and magnetic fields, if $\tau_{n\bar{n}'} < 10^3$ s

$E = 2m_n c^2 = 3 \times 10^{-3}$ erg
per every $\bar{n}$ annihilation

Two civilisations can agree to built scientific reactors and exchange neutrons ... ... we could get plenty of energy out of dark matter !

E.g. source with 3×10^{17} n/s (PSI) $\longrightarrow$ power $= 100$ MW

Asimov Machine: the "Pump"



First Part: Against Stupidity ...

Second Part: ...The Gods Themselves ...

Third Part: ... Contend in Vain?

"Mit der Dummheit kämpfen Götter selbst vergebens!" – Friedrich Schiller

Radiochemist Hallam constructs the "Pump": a cheap, clean, and apparently endless source of energy functioning by the matter exchange between our universe and a parallel universe ....
His "discovery" was inspired by beings of "parallel" universe where stars were old and became too cold – they had no more energy resources ...

Movement V *Allegro in 6/8 ft. Dies Irae*

Songe d'une nuit du sabbat

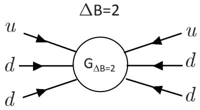
Dreaming the Sabbath of witches

He sees himself surrounded by groaning and laughing witches and demons of every kind – all have come together for his funeral. At one instant leitmotiv of the beloved appears … but this time as a vulgar dance tune which joins the Sabbath … The witches' dance is periodically intercepted by the Dies Irae in grotesque sounds

Neutron–antineutron oscillation

Neutron is a Dirac particle: $m\,\overline{n}\,n$ conserves B

Majorana mass of neutron $\frac{\epsilon}{2}(n^T C n + \bar{n}^T C \bar{n})$ $\Delta B = 2$
comes from six-fermions effective operator $\frac{1}{M^5}(udd)(udd)$



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

$\epsilon \sim \frac{\Lambda_{\rm QCD}^6}{M^5} \sim \left(\frac{1\ \rm PeV}{M}\right)^5 \times 10^{-25}$ 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

$n - \bar{n}$ oscillation: Free (or bound)

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

$$H = \begin{pmatrix} m + \mu \vec{B}\vec{\sigma} - V_n & \epsilon \\ \epsilon & m - \mu \vec{B}\vec{\sigma} - V_{\bar{n}} \end{pmatrix}$$

Free oscillation probability $P_{n\bar{n}}(t) = \frac{\epsilon^2}{\omega_B^2} \sin^2(\omega_B\, t), \quad \omega_B = \mu B$

$\omega_B t < 1 \;\; \rightarrow \;\; P_{n\bar{n}}(t) = (\epsilon t)^2 = (t/\tau_{n\bar{n}})^2$

$\omega_B t \gg 1 \;\; \rightarrow \;\; P_{n\bar{n}}(t) = \frac{1}{2}(\epsilon/\omega_B)^2 < \frac{(\epsilon t)^2}{(\omega_B t)^2}$

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

Baldo-Ceolin et al, 1994 (ILL, Grenoble) : $t \simeq 0.1$ s, $B < 1$ mG

$P_{n\bar{n}}(t) = (t/\tau_{n\bar{n}})^2 < 10^{-18} \quad \longrightarrow \quad \epsilon < 7.7 \times 10^{-24}$ eV

Neutrons in nuclei: $\omega_B \rightarrow V_{\bar{n}} - V_n \sim 100$ MeV

Can neutron be transformed into antineutron … more effectively?

Small Majorana mass of neutron $\frac{\epsilon}{2}\left(n^T C n + \overline{n} C \overline{n}^T\right) = \frac{\epsilon}{2}\left(\overline{n_c}\, n + \overline{n}\, n_c\right)$
$\equiv \quad n - \bar{n}$ oscillation $\;(\Delta B = 2)$

Oscillation probability for free flight time t
$P_{n\bar{n}}(t) = (\epsilon\, t)^2 = (t/\tau_{n\bar{n}})^2$ in quasi-free regime $\omega_B t < 1$

Present bounds on oscillation time $\tau_{n\bar{n}} = \epsilon^{-1}$ are severe:
$\tau_{n\bar{n}} > 0.86 \times 10^8$ s direct limit (free n) ILL, 1994
$\tau_{n\bar{n}} > 2.7 \times 10^8$ s nuclear stability (bound n) SK, 2020 (this conf.)

$$P_{n\bar{n}}(t) = \frac{t^2}{\tau_{n\bar{n}}^2} = \left(\frac{10^8 \text{ s}}{\tau_{n\bar{n}}}\right)^2 \left(\frac{t}{0.1 \text{ s}}\right)^2 \times 10^{-18}$$

Shortcult through mirror world: $n \to n' \to \bar{n}$:
Experimental search to be tuned against (dark) environmental conditions

$$P_{n\bar{n}}(t) = P_{nn'}(t) P_{n\bar{n}'}(t) = \frac{t^4}{\tau_{nn'}^2 \tau_{n\bar{n}'}^2} = \left(\frac{1 \text{ s}^2}{\tau_{nn'}\tau_{n\bar{n}'}}\right)^2 \left(\frac{t}{0.1 \text{ s}}\right)^4 \times 10^{-4}$$

No danger for nuclear stability !

If discovered, a potential source of enormous free energy !

$2 \times 2 = 4$!

Z.B., Eur.Phys.J C81:33 (2021), arXiv:2002.05609

4 states: $n, \bar{n} \; : \; n', \bar{n}'$ and mixing combinations:

$n \longleftrightarrow \bar{n}$ $(\Delta B = 2)$ & $n' \longleftrightarrow \bar{n}'$ $(\Delta B' = 2)$

$n \longleftrightarrow n'$ $+$ $\bar{n}' \longleftrightarrow \bar{n}$ $\Delta(B - B') = 0$

$n \longleftrightarrow \bar{n}'$ $+$ $n' \longleftrightarrow \bar{n}$ $\Delta(B + B') = 0$

Full Hamiltonian is 8×8:

$$\begin{pmatrix} m_n + \mu \vec{B}\vec{\sigma} & \epsilon_{n\bar{n}} & \epsilon_{nn'} & \epsilon_{n\bar{n}'} \\ \epsilon_{n\bar{n}} & m_n - \mu \vec{B}\vec{\sigma} & \epsilon_{n\bar{n}'} & \epsilon_{nn'} \\ \epsilon_{nn'} & \epsilon_{n\bar{n}'} & m_n' + V_n' + \mu' \vec{B}'\vec{\sigma} & \epsilon_{n\bar{n}} \\ \epsilon_{n\bar{n}'} & \epsilon_{nn'} & \epsilon_{n\bar{n}} & m_n' + V_n' - \mu' \vec{B}'\vec{\sigma} \end{pmatrix}$$

Present bounds on oscillation time $\tau_{n\bar{n}} = \epsilon^{-1}$:

$\tau_{n\bar{n}} > 0.86 \times 10^8$ s (free n), $\tau_{n\bar{n}} > 4.7 \times 10^8$ s (bound n)

$$P_{n\bar{n}}(t) = \frac{t^2}{\tau_{n\bar{n}}^2} = \left(\frac{10^8 \text{ s}}{\tau_{n\bar{n}}}\right)^2 \left(\frac{t}{0.1 \text{ s}}\right)^2 \times 10^{-18}$$

Shortcut for $n \to \bar{n}$ via $n \to n' \to \bar{n}$

Consider case when direct $n - \bar{n}$ mixing simply absent: $\epsilon_{n\bar{n}} = 0$

Anyway, $n \to \bar{n}$ emerges as second order effect via $n \to n'\bar{n}' \to \bar{n}$

$$\overline{P}_{n\bar{n}} = \overline{P}_{nn'}\overline{P}_{n\bar{n}'}$$

$$\overline{P}_{nn'} = \frac{2\epsilon^2_{nn'}\cos^2(\beta/2)}{(\Omega-\Omega')^2} + \frac{2\epsilon^2_{nn'}\sin^2(\beta/2)}{(\Omega+\Omega')^2}, \quad \overline{P}_{n\bar{n}'} = \frac{2\epsilon^2_{n\bar{n}'}\sin^2(\beta/2)}{(\Omega-\Omega')^2} + \frac{2\epsilon^2_{n\bar{n}'}\cos^2(\beta/2)}{(\Omega+\Omega')^2}$$

where β is the (unknown) angle between the vectors $\vec{B}$ and $\vec{B}'$

Disappearance experiments measure the sum $P_{nn'} + P_{n\bar{n}'} \propto \epsilon^2_{nn'} + \epsilon^2_{n\bar{n}'}$

$n - \bar{n}$ transition measures the product $P_{n\bar{n}} = P_{nn'}P_{n\bar{n}'} \propto \epsilon^2_{nn'}\epsilon^2_{n\bar{n}'}$

From the ILL'94 limit $P_{n\bar{n}} < 10^{-18}$ (measured at $B = 0$) we get

$$\tau_{nn'}\,\tau_{n\bar{n}'} > \frac{2\times 10^9}{\Omega'^2} \approx \left(\frac{0.5\,\mathrm{G}}{B'}\right)^2 \times 100\ \mathrm{s}^2$$

E.g. $\tau_{nn'}\,\tau_{n\bar{n}'} \sim 1$ second is possible if $B' \sim 5$ G

Limits become even weaker if $\Delta m > 0.1$ neV

How good the shortcut can be?

Assuming e.g. $\tau_{nn'}\,\tau_{n\bar{n}'} = 100$ s and $B' = 0.5$ G, we see that ILL94-like measurement at $B = 0.45$ G (or $B = 0.49$ G) would give $P_{n\bar{n}} \simeq \sin^2\beta \times 10^{-15}$ (or $P_{n\bar{n}} \simeq \sin^2\beta \times 10^{-12}$)

To maximalize $n - \bar{n}$ probability, one has to match resonance with about 1 mG precision: we get

$$P_{nn'}(t) = \left(\frac{t}{\tau_{nn'}}\right)^2 \cos^2\frac{\beta}{2}, \qquad P_{n\bar{n}'}(t) = \left(\frac{t}{\tau_{n\bar{n}'}}\right)^2 \sin^2\frac{\beta}{2}$$

and

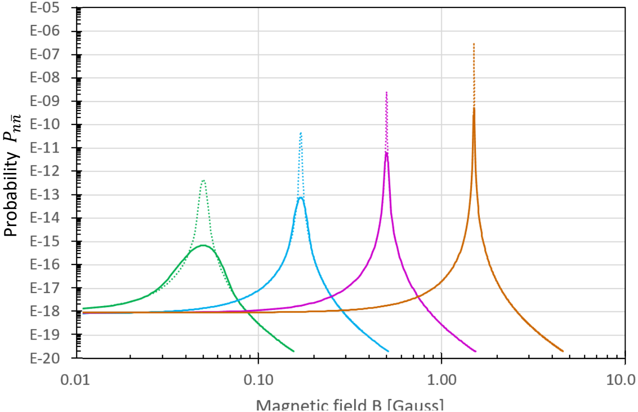
$$P_{n\bar{n}}(t) = P_{nn'}(t)P_{n\bar{n}'}(t) = \frac{\sin^2\beta}{4}\left(\frac{t}{0.1\ \mathrm{s}}\right)^4\left(\frac{100\ \mathrm{s}^2}{\tau_{nn'}\tau_{n\bar{n}'}}\right)^2 \times 10^{-8}$$

Practically no limit from nuclear stability

E.g. ^{16}O decay time predicted $\sim 10^{60}$ yr vs. present limit $\sim 10^{32}$ yr !

How effective $n \to \bar{n}$ can be?

simulations for $n - \bar{n}$ experiment with
$t = 0.1$ s ($\ell = 100$ m as ILL) and $t = 0.02$ s ($\ell = 20$ m)

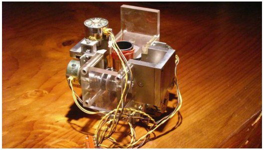


– and perhaps a chance for free energy ?

Majorana Machine

Che cretini! Hanno scoperto il protone neutro e non se ne accorgono!

La fisica è su una strada sbagliata. Siamo tutti su una strada sbagliata...



La fantomatica macchina forse teorizzata da Ettore Majorana! Nella sua formulazione attuale violerebbe un'infinità di principi scientifici, producendo enormi quantità di energia a costo zero. Non può affatto esistere ...

Anthrophic

Is the Universe Anthropic? multiverse...

or Anthropomorphic? has basic instincts ...

or Anthrophilic? has sapience and purposes ...

Neutron, proton, electron mass conspiracy: $m_e < m_n - m_p$ etc.
– free neutron decays but it becomes stable when bound in nuclei

Taken Standard Model with all coupling constants fixed in UV, sort of "explanation" why $M_W \sim 10^2$ GeV

$M_W < 10$ GeV $\longrightarrow m_e > m_n - m_p$ hydrogen atom decays $pe \to n\nu$

$M_W > 10^3$ GeV $\longrightarrow m_n > m_p + m_e + E_b$ only hydrogen, no nuclei

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

Nuclear instability against
$(A, Z) \to (A-1, \bar{n}, Z) \to (A-2, Z/Z-1) + \pi$'s scales as
Scale of new physics unknown – but $\tau_{\rm nucl} \propto \epsilon^2 \propto 1/M^{10}$ $(\epsilon \propto 1/M^5)$

Present limit $\tau_{\rm nucl} > 10^{32}$ yr implies
$\epsilon < 2.5 \times 10^{-24}$ eV $\longrightarrow$ $M > 500$ TeV or so

$M \to M/3$ (just 3 times less) would give $\tau_{\rm nucl} \to \tau_{\rm nucl}/3^{10} \approx 10^{27}$ yr

$\bar{n}n$ ($\bar{n}p$) annihilation releases energy $E_{\rm ann} = 2m_n c^2 \approx 3 \times 10^{-10}$ J

Then the Earth power $= E_{\rm ann} N_\oplus / \tau_{\rm nucl} \simeq 10$ TW
.. the Earth radioactivity turns dangerous for the Life!

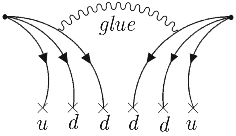
And (happily) the neutron is not elementary particle
– in which case it could have unsuppressed Majorana mass $\varepsilon n^T C n$
It is composite $n = (udd)$ of three quarks – Majorana mass
can be induced only by D=9 operator $\frac{1}{M^5}(udd)^2$
Life is permitted due to the structure of the SM

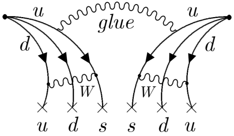
Anthropic θ-term in QCD (a provocation)

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-violating
namely $\langle (udd)^2 \rangle$ or $\langle (uds)^2 \rangle$ causing $n - \bar{n}$, $\Lambda - \overline{\Lambda}$ mixings



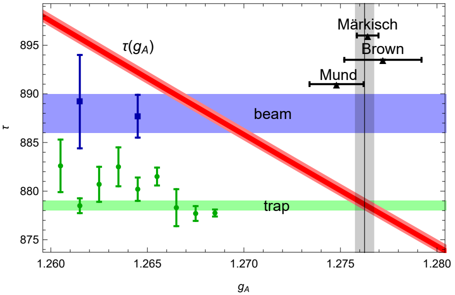


Vafa-Witten theorem: QCD cannot break vector symmetries ...
.. the prove relies on the absence of θ-term (i.e. valid for $\theta = 0$)
Imagine world $\theta \sim 1$ where $\langle qqqqqq \rangle \sim \Lambda^9_{\rm QCD}$ – bad for Life
– large $n - \bar{n}$, Goldstone β inducing $n \to \bar{n} + \beta$ in nuclei ...

Let us assume $\langle qqqqqq \rangle_\theta \sim F(\theta)\, \Lambda^9_{\rm QCD}$ with
$F(\theta)$ smooth periodic even function: $F(\theta) \simeq \cos\theta \simeq \theta^2 + \ldots$
Then for $\theta \sim 10^{-10}$, $\langle qqqqqq \rangle_\theta = \theta^2 \Lambda^9_{\rm QCD} \sim (1\ {\rm MeV})^9$
– can such a fuzzy condensate be OK? Maybe in dense matter?

Back to trap-beam problem: τ_n vs. β-asymmetry

Updated Fig.7 from Belfatto, Beradze and Z.B, EPJ C 80, 149 (2020)



$g_A = 1.27625(50)$

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

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

Free neutron decay:

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

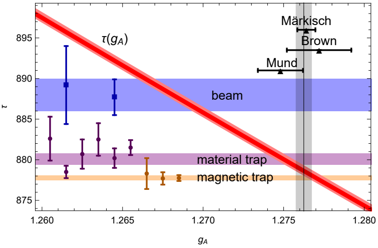
$0^+ - 0^+$ decays:

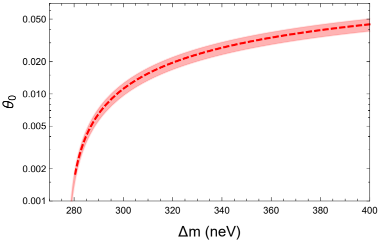
$$G_V^2 = \frac{K}{2\mathcal{F}t\,(1+\Delta_R)}$$

$$\tau_n = \frac{2\mathcal{F}t}{\mathcal{F}_n(1+3g_A^2)} = \frac{5172.1(1.1 \to 2.8)}{1+3g_A^2}\ \text{s}$$ Czarnecki et al. 2018

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

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





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

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

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

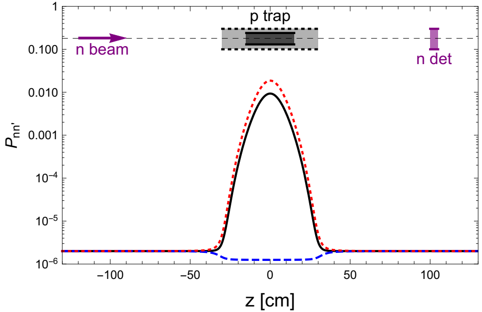
So experimentally we have $\quad \tau_{\rm magn} < \tau_{n\to p}^{\rm theor} < \tau_{\rm mat} < \tau_{\rm beam}$

which is possible in $n - n'$ oscillation scenario $\qquad$ So far so Good!

Dark matter Factory ?

If my hypothesis is correct, a simple solenoid (magn. field $\sim$ Tesla) can be an effective machine transforming neutrons into DM neutrons

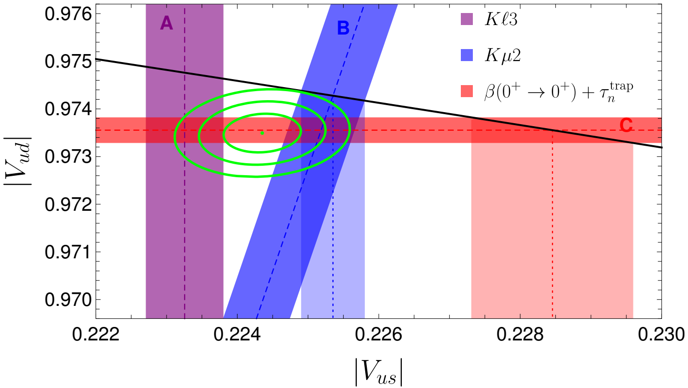
With good adiabatic conditions 50 % transformation can be achieved



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

ORNL experiment via $n \to n' \to n$ in strong magn. fields

Cabibbo Angle Anomaly



If CKM unitarity is assumed – strong discrepancy between

A: $|V_{us}| = \sin\theta_C$

B: $|V_{us}/V_{ud}| = \tan\theta_C$ Unitarity excluded at $> 3\sigma$

C: $|V_{ud}| = \cos\theta_C$