Can antimatter be produced in cosmos – and (perhaps) in laboratory?

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Contents

Introduction

Everything can be explained by the Standard Model !

... but there should be more than one Standard Models

Bright & Dark Sides of our Universe

- $\Omega_B \simeq 0.05$ observable matter: electron, proton, neutron !
- $\Omega_D \simeq 0.25$ dark matter: WIMP? axion? sterile ν? ...
- $\Omega_\Lambda \simeq 0.70$ dark energy: Λ-term? Quintessence? ....
- $\Omega_R < 10^{-3}$ relativistic fraction: relic photons and neutrinos

Matter – dark energy *coincidence:* $\Omega_M/\Omega_\Lambda \simeq 0.45$, $(\Omega_M = \Omega_D + \Omega_B)$
$\rho_\Lambda \sim$ Const., $\rho_M \sim a^{-3}$; *why* $\rho_M/\rho_\Lambda \sim 1$ – *just Today?*
Antrophic explanation: if not *Today*, then *Yesterday* or *Tomorrow.*

Baryon and dark matter *Fine Tuning:* $\Omega_B/\Omega_D \simeq 0.2$
$\rho_B \sim a^{-3}$, $\rho_D \sim a^{-3}$: *why* $\rho_B/\rho_D \sim 1$ - *Yesterday Today & Tomorrow?*

Baryogenesis requires BSM Physics: (GUT-B, Lepto-B, AD-B, EW-B ...)

Dark matter requires BSM Physics: (Wimp, Wimpzilla, sterile ν, axion, ...)

Different physics for B-genesis and DM?
Not very appealing: looks as Fine Tuning

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

Visible matter from Baryogenesis

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

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

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: $\quad \rho_D = n_X m_X$, but $\quad m_X = ?$, $\quad n_X = ?$

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

Dark Matter from a Parallel World

Our observable particles: (Best of the possible Worlds ....)
$G = SU(3) \times SU(2) \times U(1)$ (+ SUSY ? + GUT ? ...)
electron, nucleons (quarks), neutrinos, gluons, Higgs
QED photon/long range, QCD gluons/confining, Weak W, Z/short range
... matter *vs.* antimatter (CP + B/B-L violation ...)
... existence of nuclei, atoms, molecules .... life.... Homo Sapiens !

Dark matter: a parallel sector ? (Best of the possible Dark Worlds ...)
$G' = SU(3)' \times SU(2)' \times U(1)'$? (+ SUSY ? GUT '? Seesaw ?)
... dark matter (CP + B′/B′-L′ violation ...) ?
... existence of dark nuclei, atoms, molecules ... life ... Homo Aliens ?

Call it Yin-Yang (in chinise, dark-bright) duality

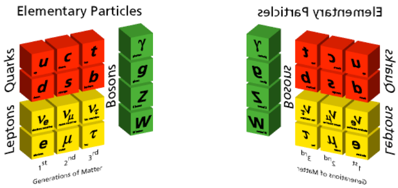
describes a philosophy how opposite forces are actually complementary, interconnected and interdependent in the natural world, and how they give rise to each other as they interrelate to one another.

$E_8 \times E_8'$

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

$G \quad \times \quad G'$

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? ($\mathcal{L}_{\rm mix} \rightarrow$ portals)
- MM is similar to standard matter, (asymmetric/dissipative/atomic) but realized in somewhat different cosmological conditions ($T'/T \ll 1$)
- $G \rightarrow G'$ 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

Twin antifermions/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

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

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

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

– Sign of baryon asymmetry (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 of M sector – so all remains academic ...

But switching on cross-interactions, violating B and B$'$ – but conserving say B+B$'$ as e.g. neutron–mirror neutron $(n - n')$ mixing: $\epsilon \bar n n' + \mathrm{h.c.}$
$Z_2^{LR} \to \mathcal{B}' = 1 \quad \to \quad n' \to n$ M matter $\to$ O matter
$Z_2 \to \mathcal{B}' = -1 \quad \to \quad \bar n' \to \bar n$ M (anti)matter $\to$ O antimatter

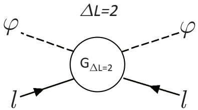
Chapter I

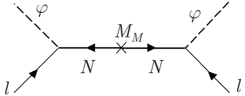
Neutrino – mirror neutrino mixings

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

- $\frac{A}{M}(\ell\phi)(\ell\phi)$ $(\Delta L = 2)$ – neutrino (seesaw) masses $m_\nu \sim v^2/M$

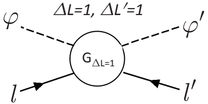
M is the (seesaw) scale of new physics beyond EW scale.





- Neutrino -mirror neutrino mixing – (active - sterile mixing)

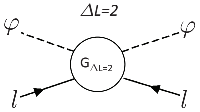
L and L' violation: $\frac{A}{M}(\ell\phi)(\ell\phi)$, $\frac{A}{M}(\ell'\phi')(\ell'\phi')$ and $\frac{B}{M}(\ell\phi)(l\ell'\phi')$

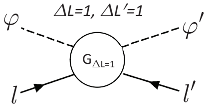


Mirror neutrinos naturally sterile neutrinos: $\langle\phi'\rangle/\langle\phi\rangle \sim 10 \div 10^2$

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.

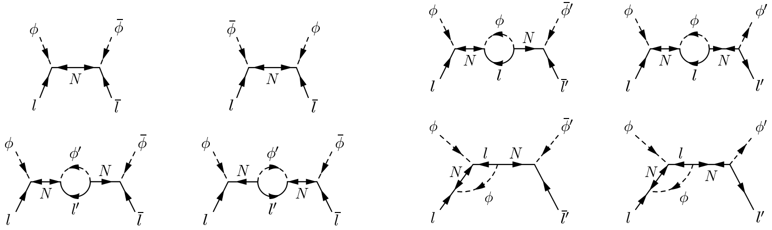
- These processes should be out-of-equilibrium
- Violate baryon numbers in both worlds, $B - L$ and $B' - L'$
- Violate also CP, given complex couplings

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 $\frac{1}{2}Mg_{jk}N_jN_k + \mathrm{h.c.}$



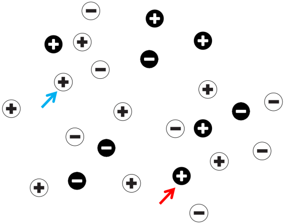
Complex Yukawa couplings $Y_{ij}l_iN_j\bar{\phi} + Y'_{ij}l'_iN_j\bar{\phi}' + \mathrm{h.c.}$

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

Co-leptogenesis: Mirror Matter as Dark Anti-Matter

Z.B., arXiv:1602.08599

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



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

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

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

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

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

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

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

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 $\quad \to \quad n_{BL} = n'_{BL}$

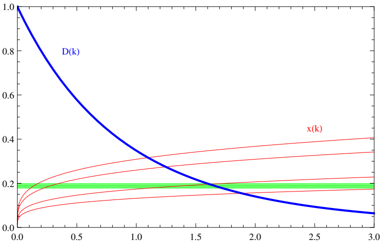
$$\Omega'_B = \Omega_B \simeq 10^3 \frac{J M_{Pl} T_R^3}{M^4} \simeq 10^3 J \left(\frac{T_R}{10^{11}\ {\rm GeV}}\right)^3 \left(\frac{10^{13}\ {\rm GeV}}{M}\right)^4$$

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

Chapter II

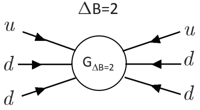
Neutron – mirror neutron mixing

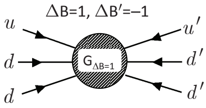
B violating operators between O and M particles in $\mathcal{L}_{\rm mix}$

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)

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

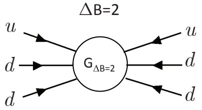




Oscillations $n \to \bar{n}$ $(\Delta B = 2)$
Oscillations $n \to \bar{n}'$ $(\Delta B = 1,\ \Delta B' = -1)$ $B + B'$ is conserved

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

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

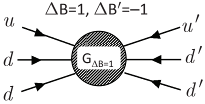
Key moment: *$n - \bar{n}$ oscillation destabilizes nuclei:*
$(A, Z) \to (A-1, \bar{n}, Z) \to (A-2, Z/Z-1) + \pi$'s

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

Neutron – mirror neutron mixing

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



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

Key observation: *$n - \bar{n}'$ oscillation cannot destabilise nuclei:*
$(A, Z) \rightarrow (A-1, Z) + n'(p'e'\bar{\nu}')$ *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 $n \rightarrow \bar{n}'$ and regeneration $n \rightarrow \bar{n}' \rightarrow n$
can be searched at small scale ‘Table Top’ experiments

Neutron – mirror neutron oscillation probability

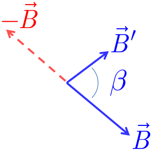
$$H = \begin{pmatrix} m_n + \mu_n \mathbf{B}\sigma & \epsilon \\ \epsilon & m_n + \mu_n \mathbf{B}'\sigma \end{pmatrix}$$

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

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

Earth mirror magnetic field via the electron drag mechanism

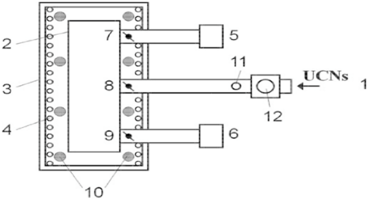
Earth can accumulate some, even tiny amount of mirror matter due to Rutherford-like scattering of mirror matter due to photon-mirror photon kinetic mixing.
Rotation of the Earth drags mirror electrons but not mirror protons (ions) since the latter are much heavier.
Circular electric currents emerge which can generate magnetic field.
Modifying mirror Maxwell equations by the source (drag) term, one gets $B' \sim \epsilon^2 \times 10^{15}$ G before dynamo, and even larger after dynamo.

Such mechanism can also induce cosmological magnetic fields
Z.B., Dolgov, Tkachev, 2013

Experimental Strategy

To store neutrons and to measure if the amount of the survived ones depends on the magnetic field applied.

- Fill the Trap with the UCN
- Close the valve
- Wait for T_S (300 s ...)
- Open the valve
- Count the survived Neutrons



Repeat this for different orientation and values of Magnetic field.

$N_B(T_S) = N(0)\exp\left[-\left(\Gamma + R + \bar{\mathcal{P}}_B \nu\right) T_S\right]$

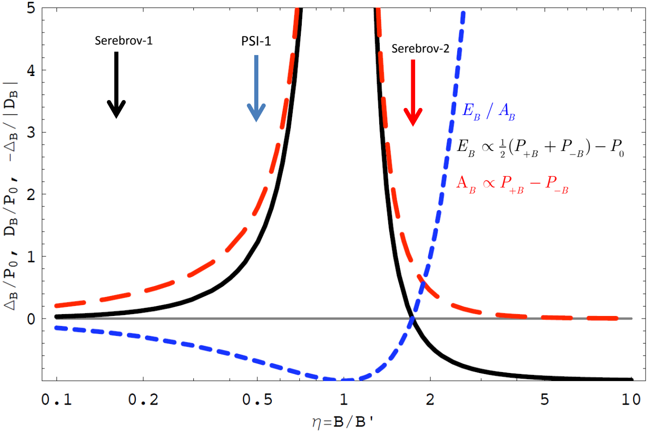
$$\frac{N_{B1}(T_S)}{N_{B2}(T_S)} = \exp\left[\left(\bar{\mathcal{P}}_{B2} - \bar{\mathcal{P}}_{B1}\right)\nu T_S\right]$$

So if we find that:

$$A(B, T_S) = \frac{N_B(T_S) - N_{-B}(T_S)}{N_B(T_S) + N_{-B}(T_S)} \neq 0 \qquad E(B, b, T_S) = \frac{N_B(T_S)}{N_b(T_S)} - 1 \neq 0$$

A and E are expected to depend on magnetic field

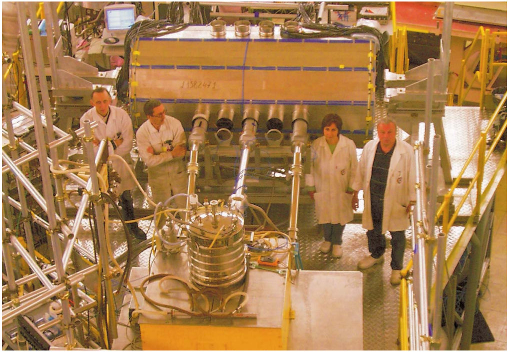
E.g. assume B'=0.12 Gauss



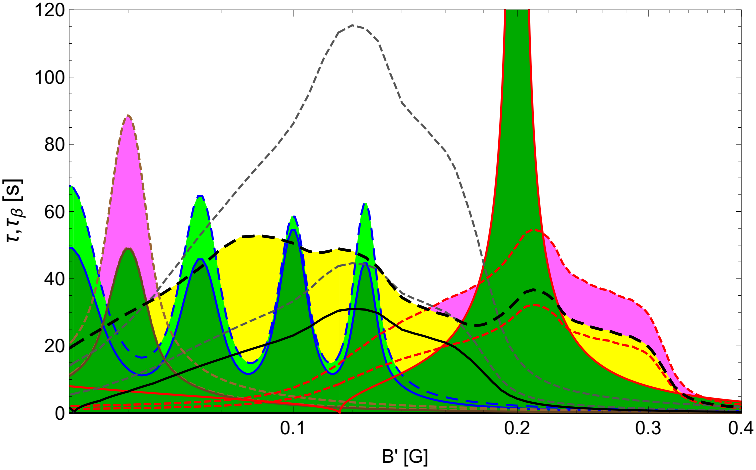
Experiments

8 experiment were done at ILL/PSI, 3+1 by PSI group, 2+1 by Serebrov group with 190 l beryllium plated trap for UCN

New experiments are underway at PSI, ILL and ORNL



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



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) Neutron Stars – conversion of NS into mixed ordinary/mirror NS

Chapter IV

$n - n'$ and Neutron Stars (and Mirror Neutron stars)

Z.B., Biondi, Mannarelli, Tonelli, arXiv:2012.15233

Z.B., arXiv:2106.11203

Neutron Stars: $n - n'$ conversion

Two states, n and n'

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

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

$V_n = 2\pi a n_b/m_n \simeq \xi a_3 \times 125$ MeV $\quad \xi = n_b/n_s$ $(n_s = 0.16/\text{ fm}^3)$

$E_F \simeq \xi^{2/3} \times 60$ MeV, $\quad (V'_n < V_n, \quad E'_F < E'_F)$

$nn \to nn'$ with rate $\Gamma = 2\theta^2 \eta \langle \sigma v \rangle n_b$, $\quad \sigma = 4\pi a^2$

$\frac{dN}{dt} = -\Gamma N \quad \frac{dN'}{dt} = \Gamma N \quad N + N' = N_0$ 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

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

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

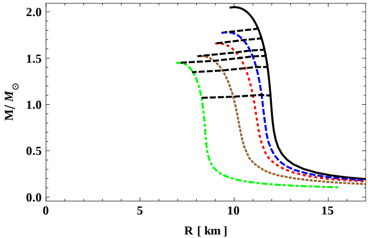
$$\rho = \rho_1 + \rho_2 \ \&\ p = p_1 + p_2, \qquad p_\alpha = F(\rho_\alpha)$$

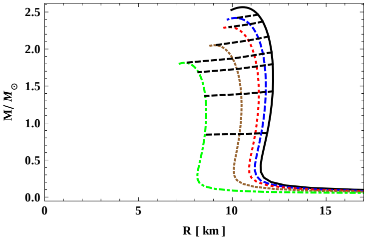
$$\frac{dm}{dr} = 4\pi r^2 \rho \ \to\ \frac{dm_{1,2}}{dr} = 4\pi r^2 \rho_{1,2} \qquad m = m_1 + m_2$$

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

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

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



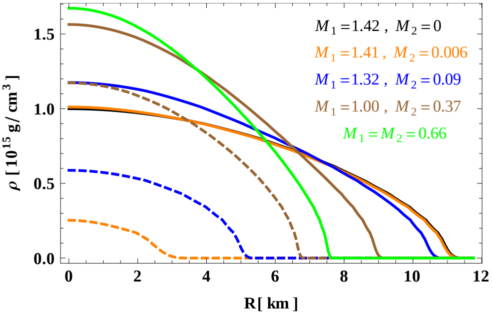


$\sqrt{2}$ rule: $\quad M^{\rm max}_{\rm mix} = \frac{1}{\sqrt{2}} M^{\rm max}_{\rm NS} \qquad R_{\rm mix}(M) = \frac{1}{\sqrt{2}} R_{\rm NS}(M)$

Neutron Star transformation

$\frac{dN}{dt} = -\Gamma N \qquad \frac{dN'}{dt} = \Gamma \qquad N + N' = N_0$ 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: observational $M - R$

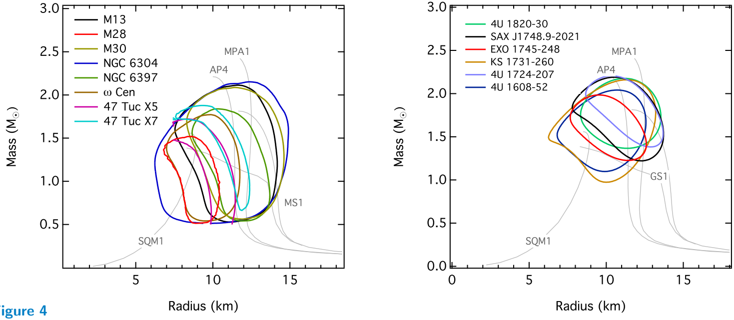
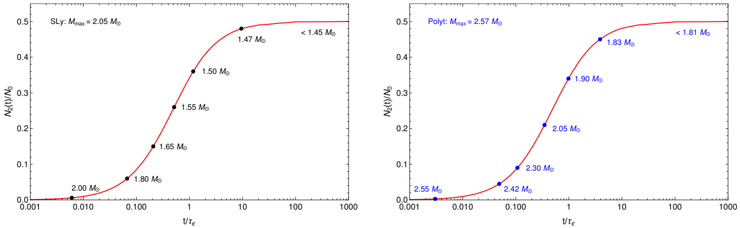


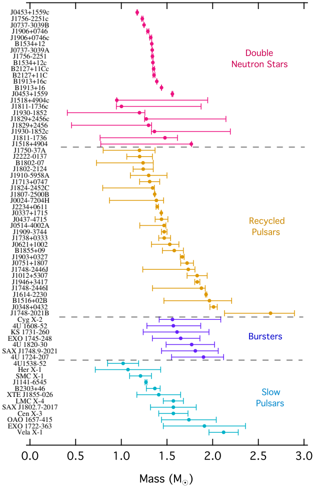
Figure 4

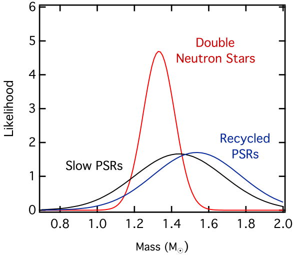
The combined constraints at the 68% confidence level over the neutron star mass and radius obtained from (Left) all neutron stars in low-mass X-ray binaries during quiescence (Right) all neutron stars with thermonuclear bursts. The light grey lines show mass-relations corresponding to a few representative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

Neutron Stars Evolution to mixed star



Neutron Stars: mass distribution



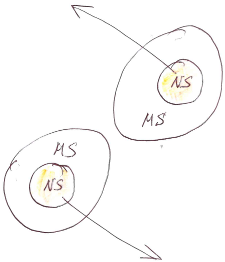


Neutron Star Mergers

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 normal matter or antimatter (depends on the mirror BA sign) – their mergers can be origin of antinuclei for AMS-2



Antimatter Cores in Mirror Neutron stars

DUPOURQUÉ, TIBALDO, and VON BALLMOOS PHYS. REV. D **103,** 083016 (2021)

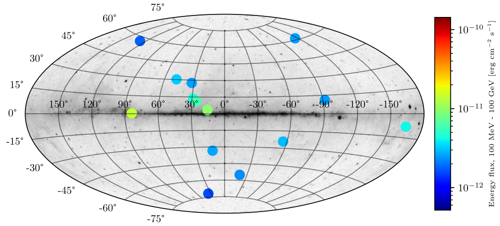


FIG. 1. Positions and energy flux in the 100 MeV–100 GeV range of antistar candidates selected in 4FGL-DR2. Galactic coordinates. The background image shows the *Fermi* 5-year all-sky photon counts above 1 GeV (image credit: NASA/DOE/Fermi LAT Collaboration).

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:

$J \simeq \frac{10^{-12}}{v_{100}^3} \left(\frac{n_{\rm is}}{1/\mathrm{cm}^3}\right) \left(\frac{M}{1.5\, M_\odot}\right)^2 \left(\frac{50\,\mathrm{pc}}{d}\right)^2 \frac{\mathrm{erg}}{\mathrm{cm}^2 \mathrm{s}}$ $\quad d$ – 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 opposite signs: $B > 0$ i.e. $B' < 0$. Since $B + B'$ is conserved, our neutrons have transition $n \to n'$ (n' is antiparticle for the mirror observer) while $\bar{n}'$ (part of M matter) oscillates $\bar{n}' \to \bar{n}$ into our antineutron

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

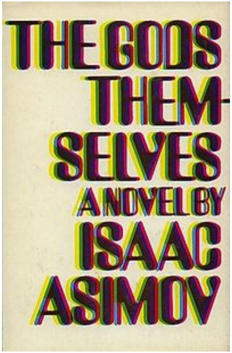
dark neutrons, before they decay, can be effectively transformed into our antineutrons in controllable way, by tuning vacuum and magnetic fields, if $\tau_{n\bar{n}'} < 10^3$ s

... 3×10^{-3} erg per every $\bar{n}' \to \bar{n}$

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



First Part: Against Stupidity ...

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

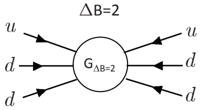
Third Part: ... Contend in Vain?

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

Neutron–antineutron oscillation

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

Majorana mass of neutron $\epsilon(n^T Cn + \bar{n}^T C\bar{n})$ violates 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

Anthrophic

Is the Universe Anthropic? multiverse...

or Anthropomorphic? has basic instincts ...

or Anthropophilic? 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 $= E_{\rm ann} N_\odot / \tau_{\rm nucl} \simeq 10$ TW
.. the Earth radioactivity turns dangerous for the Life!

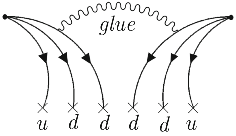
And (happily) the neutron is not elementary particle
– in which case it could have unsuppressed Majorana mass
It is composite $n = (udd)$ of three quarks – its Majorana mass
can be induced only by D=9 operator $\frac{1}{M^5}(udd)^2$ with $M \gg 200$ TeV
Life is permitted due to the structure of SM

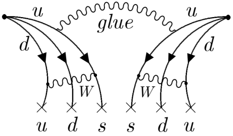
Anthropic θ-term in QCD (a provocation)

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

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

Can six-quark condensates $\langle qqqqqq \rangle$ be formed? B-violating namely $\langle (udd)^2 \rangle$ or $\langle (uds)^2 \rangle$ causing $n - \bar{n}$, $\Lambda - \bar{\Lambda}$ 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?

Free neutron– antineutron oscillation

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

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

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

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

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

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

More suppression makes no sense !

Exp. Baldo-Ceolin et al, 1994 (ILL, Grenoble) : $t \simeq 0.1$ s, $B < 100$ nT

$\tau > 0.9 \times 10^8 \quad \rightarrow \quad \epsilon < 7.7 \times 10^{-24}$ eV

$P_{n\bar{n}}(t) = (t/\tau)^2 < 10^{-18}$ for $n - \bar{n}$ tranistion probability

At ESS 10^2 times better sensitivity – down to $\epsilon \simeq 10^{-25}$ eV

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.)

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

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

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

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:

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

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

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

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

Majorana Machine: 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

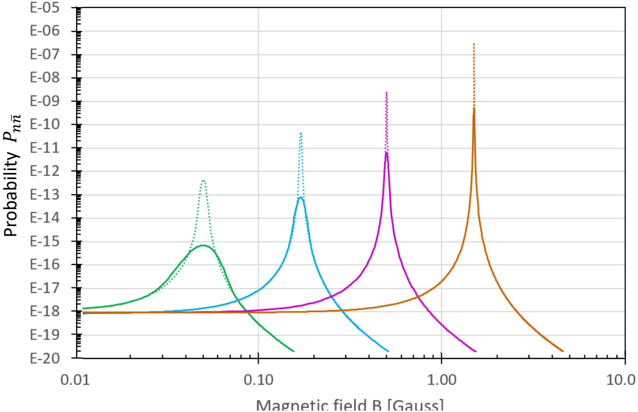
$$P_{n\bar{n}}(t) = P_{nn'}(t)P_{n\bar{n}'}(t) = \frac{\sin^2\beta}{4}\left(\frac{t}{0.1\ \mathrm{s}}\right)^4 \left(\frac{100\ \mathrm{s}^2}{\tau_{nn'}\tau_{n\bar{n}'}}\right)^2 \times 10^{-8}$$

Practically no limit from nuclear stability

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

Majorana Machine: 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 ?

In Astrophysics

Neutrons are making 1/7 fraction of baryon mass in the Universe.

But neutrons bound in nuclei cannot oscillate into mirror twins.

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

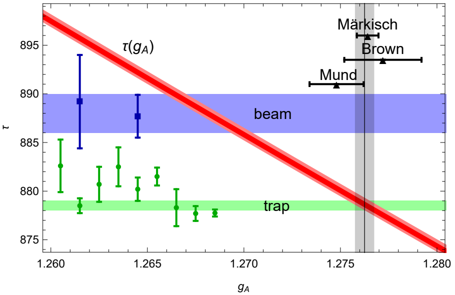
But free neutrons are present only in

- Reactors and accelerators (challenge for $\tau_{nn'} < 10^3$ s)
- In Cosmic Rays (fast $n' \to n$ can solve UHECR puzzles)
- During BBN epoch (fast $n' \to n$ vs Lithium problem ?)

$-$ Transition $n \to n'$ can take place for (gravitationally) bound n in Neutron Stars
$+$ many implications for pulsars and GW from NS-NS or NS-BH mergers
— $\bar{n}' \to \bar{n}$ n mirror neutron stars visible by γ-emission

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:

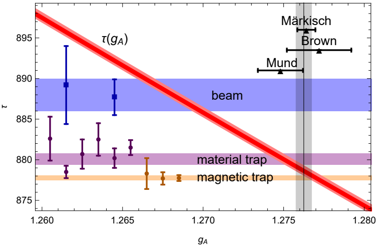
$$G_V^2 = \frac{K}{2\mathcal{F}t\,(1+\Delta_R)}$$

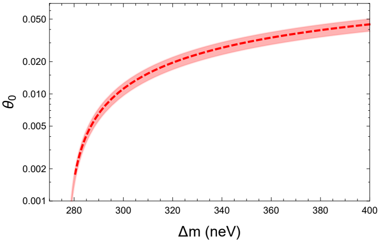
$$\tau_n = \frac{2\mathcal{F}t}{\mathcal{F}_n(1+3g_A^2)} = \frac{5172.1(1.1 \to 2.8)}{1+3g_A^2}\ \text{s}$$

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 $\quad \tau_{\rm trap} = 878.5 \pm 0.5$ s (compatible)

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

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

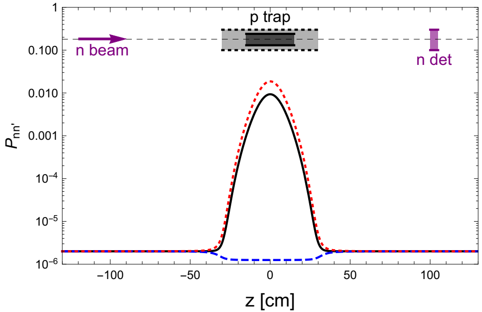
So experimentally we have $\quad \tau_{\rm magn} < \tau_{n\to p}^{\rm theor} < \tau_{\rm mat} < \tau_{\rm beam}$

which is possible in $n - n'$ oscillation scenario $\quad$ 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

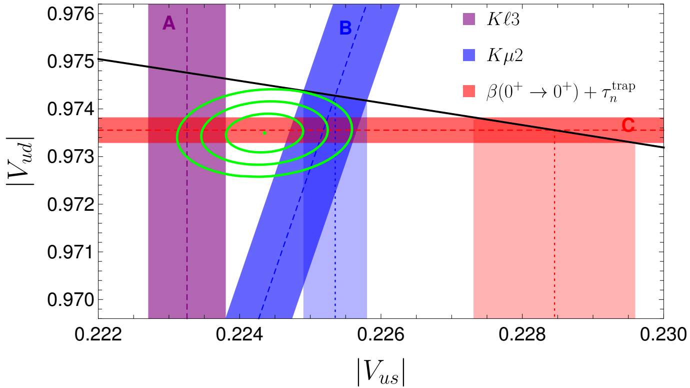
With good adiabatic conditions 50 % transformation can be achieved



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

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