New scenario for the neutron–antineutron oscillation: *shortcut through mirror world*

Zurab Berezhiani

University of L'Aquila and LNGS

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Contents

Z.B., arXiv:2002.05609 to appear in Eur. Phys. J. C

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 $\quad (\Delta B = 2)$

Oscillation probability for free flight time t

$$P_{n\bar{n}}(t) = \frac{\epsilon^2 \sin^2\left(\sqrt{\Omega^2+\epsilon^2}\; t\right)}{\Omega^2+\epsilon^2} \to (\epsilon\, t)^2 \quad \text{in quasi-free regime} \quad \Omega t \ll 1$$

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

$\tau_{n\bar{n}} > 4.7 \times 10^8$ s nuclear stability (bound n) SK, 2020 (this conf.)

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

Shortcut through mirror world: $\quad n \to n' \to \bar{n}$:

Experimental search to be tuned against (dark) environmental conditions

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

No danger for nuclear stability !

If discovered, a potential source of enormous free energy !

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 – DE *coincidence:* $\Omega_\Lambda/\Omega_M \simeq 2.5$ $(\Omega_M = \Omega_D + \Omega_B)$
Why $\rho_M/\rho_\Lambda \sim 1$ – *Today?*

if not *Today*, then *Yesterday* or *Tomorrow:* $\rho_\Lambda \sim$ Const., $\rho_M \sim a^{-3}$

Baryon –DM *Fine Tuning:* $\Omega_D/\Omega_B \simeq 5$
– *Yesterday Today & Tomorrow?* $\rho_B, \rho_D \sim a^{-3} \rightarrow \rho_B/\rho_D \sim Const.$

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 appealing: Fine Tuning ...

Dark Matter from a Parallel World

Our observable particles .... *very complex physics !!*
$G = SU(3) \times SU(2) \times U(1)$ (+ SUSY ? GUT ? Seesaw ?)
photon, electron, nucleons (quarks), neutrinos, gluons, $W^{\pm} - Z$, Higgs ...
long range EM forces, confinement scale $\Lambda_{\rm QCD}$, weak scale M_W
... matter *vs.* antimatter (B-L violation, CP ...)
... existence of nuclei, atoms, molecules .... life.... Homo Sapiens !
Best of the possible Worlds ....

Dark matter from parallel gauge sector ? Another Best World?
$G' = SU(3)' \times SU(2)' \times U(1)'$? (+ SUSY ? GUT '? Seesaw ?)
photon$'$, electron$'$, nucleons$'$ (quarks$'$), $W' - Z'$, gluons$'$?
... long range EM forces, confinement at $\Lambda'_{\rm QCD}$, weak scale M'_W ?
... asymmetric dark matter (B$'$-L$'$ violation, CP ...) ?
... existence of dark nuclei, atoms, molecules ... life ... Homo Aliens ?

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

A philosophy of opposite forces which are complementary, interconnected and interdependent in the natural world – they give rise to each other as they interrelate to one another. $E_8 \times E'_8$?

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

Fermions and anti-fermions : $\bar{\psi}_{R,L} = C\overline{\psi_{L,R}}^T$

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

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

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

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

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

B′=-1/3 L′=-1 B′=-1/3 L′=-1

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

B′=1/3 L′=1 B′=1/3 L′=1

$$\mathcal{L}_{\rm Yuk} = \bar{u}_L Y_u q_L \bar{\phi} + \bar{d}_L Y_d q_L \phi + \bar{e}_L Y_e \ell_L \phi \quad + \quad \text{h.c.}$$
$$\mathcal{L}_{\rm Yuk} = \bar{u}'_L Y'_u q'_L \bar{\phi}' + \bar{d}'_L Y'_d q'_L \phi' + \bar{e}'_L Y'_e \ell'_L \phi' \quad + \quad \text{h.c.}$$

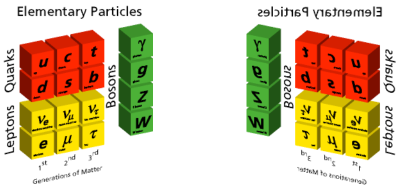
Z_2 symmetry $(L, R \to L, R)$: $Y' = Y$ $\quad B + B' \to -(B + B')$

PZ_2 symmetry $(L, R \to R, L)$: $Y' = Y^*$ $\quad B + B' \to B + B'$

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

$$G \times G'$$

Regular world — Mirror world



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

– All you need is ... M world colder than ours !

For a long time M matter was not considered as a real candidate for DM: naively assuming that exactly identical microphysics of O & M worlds implies also their cosmologies are exactly identical :

- $T' = T, \quad g'_* = g_* \quad \rightarrow \quad \Delta N_\nu^{\rm eff} = 6.15$ vs. $\Delta N_\nu^{\rm eff} < 0.5$ (BBN)
- $n'_B/n'_\gamma = n_B/n_\gamma \; (\eta' = \eta) \quad \rightarrow \quad \Omega'_B = \Omega_B$ vs. $\Omega'_B/\Omega_B \simeq 5$ (DM)

But all is OK if : Z.B., Dolgov, Mohapatra, 1995 *(broken PZ_2)*
Z.B., Comelli, Villante, 2000 *(exact PZ_2)*

A. after inflation M world was born colder than O world, $T'_R < T_R$
B. any interactions between M and O particles are feeble and cannot bring two sectors into equilibrium in later epochs
C. two systems evolve adiabatically (no entropy production): $T'/T \simeq$const

$T'/T < 0.5$ (BBN), but $T'/T < 0.2$ (CMB, LSS...)

$x = T'/T < 0.2 \quad \Longrightarrow$ in O sector 75% H + 25% ^{4}He
$\Longrightarrow$ in M world 25% H′ + 75% ^{4}He′

For broken PZ_2, DM can be compact H' atoms or n' with $m \simeq 5$ GeV or (sterile) mirror neutrinos $m \sim$ few keV Z.B., Dolgov, Mohapatra, 1995

Experimental and observational manifestations

A. *Cosmological implications.*

• Mirror baryons as asymmetric/collisional/dissipative/atomic dark matter:
– earlier H′ recombination and baryon′ acoustic oscillations, $(T'/T \ll 1)$
– Cosmic dawn? Galaxy halo as mirror elliptical galaxy? Dark matter disk? Microlensing ? Neutron stars? Binary Black Holes? Central Black Holes?
– Faster formation and evolution of stars: H' – 25%, He' – 75%

B. *Direct detection.* M matter can interact with ordinary matter e.g. via kinetic mixing $\epsilon F^{\mu\nu} F'_{\mu\nu}$, etc. Mirror hydrogen and helium as most abundant mirror matter particles (DM masses $<$ 4 GeV remain unexplored)

C. *Oscillation phenomena between ordinary and mirror particles.*
The most interesting interaction terms in $\mathcal{L}_{\rm mix}$ are the ones which violate B and L of both sectors. Neutral particles, elementary (as e.g. neutrino) or composite (as the neutron or hydrogen atom) can mix with their mass degenerate (sterile) twins: matter disappearance (or appearance) phenomena can be observable in laboratories.
In the Early Universe, these B and/or L violating interactions can give primordial baryogenesis and dark matter genesis, with $\Omega'_B/\Omega_B = 1 \div 5$.

Possible portals to Mirror World: $\mathcal{L}_{\rm mix}$

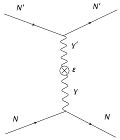
these terms can be limited (only) by experiment/cosmology !

- Kinetic mixing of photons $\epsilon F^{\mu\nu} F'_{\mu\nu}$

Makes mirror matter nanocharged ($q \sim \epsilon$)

$\epsilon < 3 \times 10^{-8}$ (EXP) $\quad \epsilon < 5 \times 10^{-9}$ (COSM)

GUT: $\frac{1}{M^2}(\Sigma G^{\mu\nu})(\Sigma' G'_{\mu\nu}) \quad \epsilon \sim \left(\frac{M_{GUT}}{M}\right)^2$



Can induce galactic magnetic fields Z.B., Dolgov, Tkachev, 2013

- Higgs-Higgs′ coupling $\lambda(\phi^\dagger\phi)(\phi'^\dagger\phi')$

$\lambda < 10^{-7}$ (COSM)

SUSY: $\frac{1}{M}(\phi_1\phi_2)(\phi'_1\phi'_2)$

$\lambda \sim M_{\rm SUSY}/M$

or NMSSM (Twin Higgs)

$\lambda S(\phi_1\phi_2 + \phi'_1\phi'_2) + \Lambda S + \ldots$

- Neutrino-neutrino′ (active-sterile) mixing – discussed later

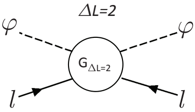
- Neutron-neutron′ mixing – discussed later

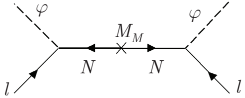
Chapter I

Neutrino – mirror neutrino mixings

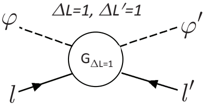
B-L violation in O and M sectors: Active-sterile mixing

- $\frac{1}{M}(\ell\bar{\phi})(\ell\bar{\phi})$ $(\Delta L = 2)$ – 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: $\frac{1}{M}(\ell\bar{\phi})(\ell\bar{\phi})$, $\frac{1}{M}(\ell'\bar{\phi}')(\ell'\bar{\phi}')$ and $\frac{1}{M}(\ell\bar{\phi})(\ell'\bar{\phi}')$



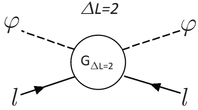
Z.B. & Mohapatra, Phys.Rev. D52 (1995)

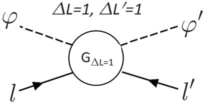
$$\begin{pmatrix} m_\nu & m_{\nu\nu'} \\ m_{\nu\nu'} & m'_\nu \end{pmatrix} = \frac{1}{M}\begin{pmatrix} v^2 & vv' \\ vv' & v'^2 \end{pmatrix}$$

Mirror neutrinos are natural candidates for sterile neutrinos

Co-leptogenesis: 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.

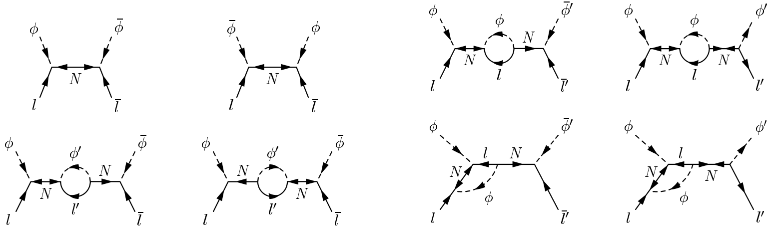
- These processes are out-of-equilibrium
- Violate baryon numbers in both worlds, $B - L$ and $B' - L'$
- Violate CP given that couplings are complex

Green light to celebrated 3 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 $\frac{1}{2}Mg_{jk}N_jN_k + \text{h.c.}$



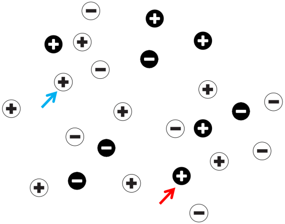
Complex Yukawa couplings $Y_{ij}l_iN_j\bar{\phi} + Y'_{ij}l'_iN_j\bar{\phi}' + \text{h.c.}$

Z_2 (Xerox) symmetry $\rightarrow Y' = Y$,
PZ_2 (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 (PZ_2): $\quad Y' = Y^* \quad \to \quad \Delta\sigma' = -\Delta\sigma \quad \to \quad B, B' > 0$

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

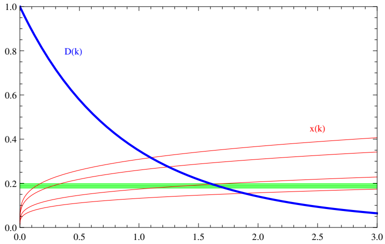
$$\Omega'_B = \Omega_B \simeq 10^3 \frac{J M_{Pl} T_R^3}{M^4} \simeq 10^3 J \left(\frac{T_R}{10^{11}\ {\rm GeV}}\right)^3 \left(\frac{10^{13}\ {\rm GeV}}{M}\right)^4$$

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.

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

should be solved with Γ:



$D(k) = \Omega_B/\Omega'_B$, $\quad x(k) = T'/T$ 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

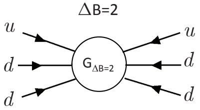
Neutron – mirror neutron mixing

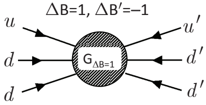
B violating operators between O and M particles in $\mathcal{L}_{\rm mix}$

Ordinary quarks $u,\ d\ (B=1/3)$ - antiquarks $\bar{u},\ \bar{d}\ (B=-1/3)$
Mirror quarks $\bar{u}',\ \bar{d}'\ (B'=1/3)$ - antiquarks $u',\ d'\ (B=-1/3)$

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

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



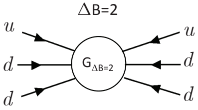


$n-\bar{n}$: $udd \to \bar{u}\bar{d}\bar{d}$ $(\Delta B = 2)$
$n-n'$: $udd \to \bar{u}'\bar{d}'\bar{d}'$ $(\Delta B=1,\ \Delta B'=-1)$ $B+B'$ conserved

Neutron– antineutron mixing

Kuzmin 1970, Marshak & Mohapatra 1980

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

$$\varepsilon = \langle n|(udd)(udd)|\bar{n}\rangle \sim \frac{\Lambda^6_{\rm QCD}}{M^5} \sim \left(\frac{100\ \rm TeV}{M}\right)^5 \times 10^{-24}\ \rm eV$$

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

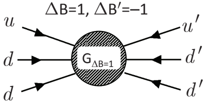
$\varepsilon < 2.5 \times 10^{-24}$ eV $\quad\to\quad$ $\tau > 2.7 \times 10^8$ s $\quad$ O, SK 2015

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

Neutron – mirror neutron mixing

ZB and Bento, PRL 96, 081801 (2006)

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



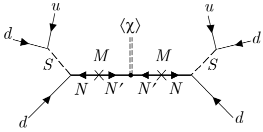
$$\epsilon = \langle n|(udd)(u'd'd')|\bar{n}'\rangle \sim \frac{\Lambda^6_{\rm QCD}}{M^5} \sim \left(\frac{1 \ \mathrm{TeV}}{M}\right)^5 \times 10^{-10} \ \mathrm{eV}$$

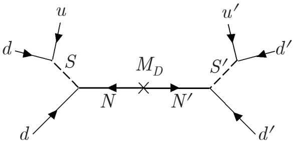
Key observation: *$n - \bar{n}'$ oscillation cannot destabilise nuclei:*
$(A, Z) \rightarrow (A-1, Z) + n'(p'e'\bar{\nu}')$ forbidden by energy conservation
(In principle, it can destabilise Neutron Stars)

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

Seesaw origin of both $n - n'$ and $n - \bar{n}$





ZB and Bento, PRL 96, 081801 (2006), ZB, Eur.Phys.J. C76 , 705 (2016)

$S\, u\, d + S^\dagger d\, \mathcal{N} + M_D \mathcal{N}\mathcal{N}' + \chi \mathcal{N}^2 + \chi^\dagger \mathcal{N}'^2$

$g_n(\chi n^T C n + \chi^\dagger n'^T C n' + \mathrm{h.c.})$

$$\epsilon_{n\bar{n}} \sim \frac{\Lambda^6_{\rm QCD} V}{M_D^2 M_S^4} \sim \left(\frac{10^8 \;\mathrm{GeV}}{M_D}\right)^2 \left(\frac{1 \;\mathrm{TeV}}{M_S}\right)^4 \left(\frac{V}{1 \;\mathrm{MeV}}\right) \times 10^{-24}\;\mathrm{eV}$$

$\tau_{n\bar{n}} > 10^8$ s

$n - n'$ oscillation with $\tau_{nn'} \sim 1$ s $\quad \tau_{nn'} \sim \frac{V}{M_D} \tau_{n\bar{n}}$

$$\epsilon_{nn'} \sim \frac{\Lambda^6_{\rm QCD}}{M_D M_S^4} \sim \left(\frac{10^8 \;\mathrm{GeV}}{M_D}\right) \left(\frac{1 \;\mathrm{TeV}}{M_S}\right)^4 \times 10^{-15}\;\mathrm{eV}$$

$M_D M_S^4 \sim (10 \;\mathrm{TeV})^5$

Free Neutrons: Where to find Them ?

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

But most of neutrons are bound in nuclei ....

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

Free neutrons are present only in

- Reactors and Spallation Facilities
- Cosmic Rays (explain discrepancies between Auger and Tel. Array)
- During BBN epoch (fast $n' \to n$ can help in Lithium problem)

– Transition $n \to \bar{n}'$ can take place for Neutron Stars
– conversion of NS into mixed ordinary/mirror NS
$M_{TS}^{\max} = M_{NS}^{\max}/\sqrt{2}$ for 50% – 50% mixed twin stars

Environmental effects:

E.g. $m'_n \neq m_n$ or mirror magnetic field B' at the Earth, etc.

Neutron and antineutron masses are equal by CPT.
But $m_n = m'_n$ is due to PZ_2 symmetry which can have small breaking
E.g. in somasymmetric reheating scenarios, Mohapatra and Nussinov, 2018

Also there can be extra forces which differently act on n and n', e.g. mirror magnetic field B'

Earth can accumulate some tiny amount of mirror matter via Rutherford-like scattering due to kinetic mixing $\epsilon F^{\mu\nu} F'_{\mu\nu}$
Vorticity: rotation of the Earth drags mirror electrons but not mirror protons (ions) which are much heavier.

Circular electric currents emerge which can generate magnetic field.
Modifying mirror MHD equations by the source (drag) term, one gets $B' \sim \epsilon^2 \times 10^{15}$ G before dynamo, and can be further amplified by th MHD dynamo, up to few Gauss ...

Relative rotation of O and M components can also induce cosmological magnetic fields Z.B., Dolgov, Tkachev, 2013

Neutron – mirror neutron oscillation probability

4×4 Hamiltonian (n and n' each with two spin states, $\vec{\sigma}$ Pauli)

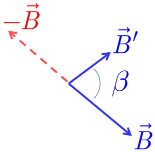
$$H = \begin{pmatrix} m_n + \mu_n \vec{B}\vec{\sigma} & \epsilon \\ \epsilon & m'_n + \mu'_n \vec{B}'\vec{\sigma} \end{pmatrix}$$

n-n' transition oscillation depends on the relative orientation of magnetic fields $\vec{B}$ and $\vec{B}'$: $2\omega = |\mu_n B|$ and $2\omega' = |\mu'_n B'|$

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

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

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



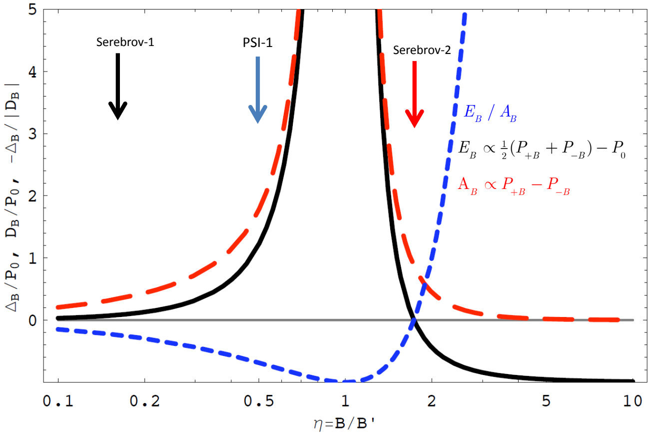
where $\omega = \frac{1}{2}\left|\mu B\right|$ and $\omega' = \frac{1}{2}\left|\mu B'\right|$; τ - oscillation time

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

Z.B., Eur. Phys. J C 64 , 421 (2009)

A and E are expected to depend on magnetic field

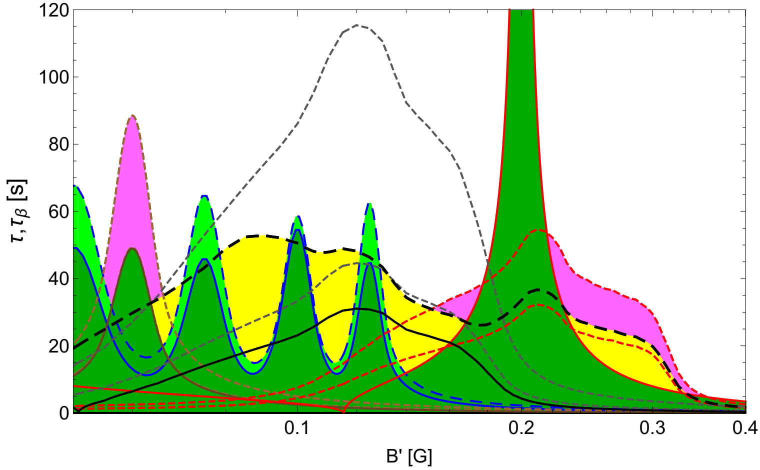
E.g. assume B'=0.12 Gauss



Exp. limits on $n - n'$ oscillation time

ZB, Biondi, Geltenbort et al, Eur. Phys. J. C. 78, 717 (2018)

$$\tau_\beta = \tau / \sqrt{|\cos\beta|}$$



$2 \times 2 = 4$! ZB, arXiv:2002.05609

4 states: n, $\bar{n}$, n', $\bar{n}'$ (2 spin states for each)

Possible mixings:

$n - \bar{n}$ $(\Delta B = 2)$ $\leftrightarrow$ $n' - \bar{n}'$ $(\Delta B' = 2)$

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

Full Hamiltonian is 8×8:

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

If mixings with mirror states $(\epsilon_{nn'}, \epsilon_{n\bar{n}'})$ are negligible

$$P_{n\bar{n}}(t) = \frac{\epsilon^2 \sin^2\left(\sqrt{\Omega^2+\epsilon^2}\; t\right)}{\Omega^2+\epsilon^2} \to (t/\tau_{n\bar{n}})^2 \quad \text{if} \quad \Omega t \ll 1, \quad \Omega = |\mu B|$$

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)

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

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

Consider case $\Delta m = m'_n - m_n = 0$ and $V'_n = 0$, but $B' \neq 0$.
(and take simply that direct $n - \bar{n}$ mixing is negligible: $\epsilon_{n\bar{n}} = 0$)

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

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

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

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 shortcut $n \to \bar{n}$ via $n \to n' \to \bar{n}$ 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 !

Short summary for Shortcut ...

A fascinating scenario of having in addition to what was above

– New B violating physics at the scale of few TeV (maybe even in LHC reach?)

– Low scale (few TeV) co-baryogenesis scenario (like in my and Bento 2006 paper but parametrically better) and ultimately identification of dark matter

– strong implications for astrophysics etc etc.

– and finally perhaps a chance for free energy ?

Thanks

E-mail: zurab.berezhiani@lngs.infn.it