Puzzling Neutron: A Window to Dark Matter?

A Detective Story in three parts

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BSM: Where do we go from here? GGI, Florence, 2-8 Sept. 2018

Contents

Useful information

Neutrons – long known particles making 50% of atomic mass in our bodies ...

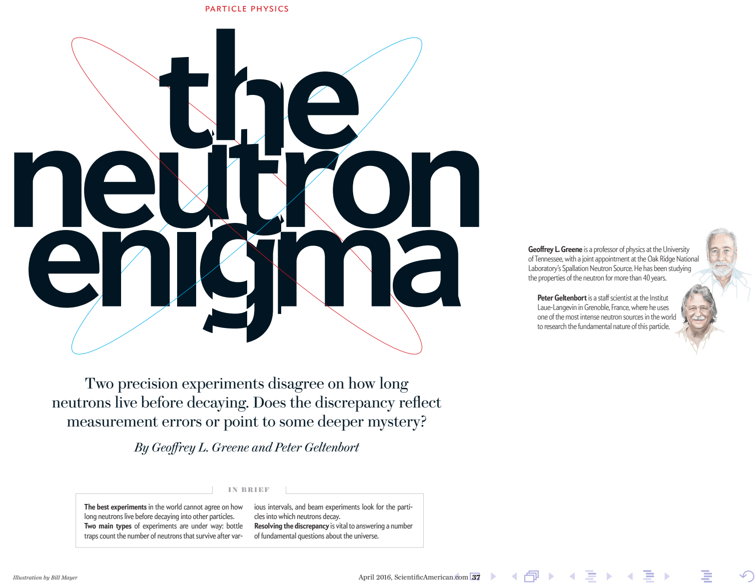
They are stable in nuclei but decay in free state as $n \to pe\bar{\nu}_e$ and in unstable nuclei (β-decay)

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

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

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

The lifetime puzzle



PARTICLE PHYSICS

the neutron enigma

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

By Geoffrey L. Greene and Peter Geltenbort

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

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

IN BRIEF

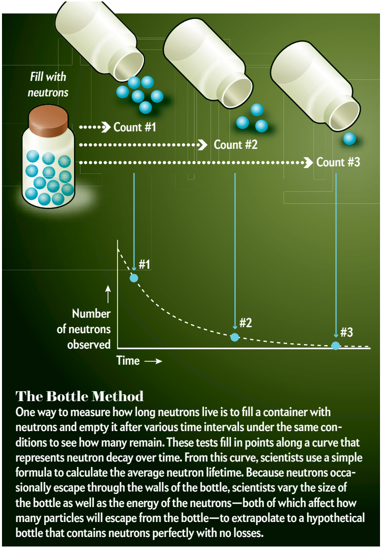
The best experiments in the world cannot agree on how long neutrons live before decaying into other particles.

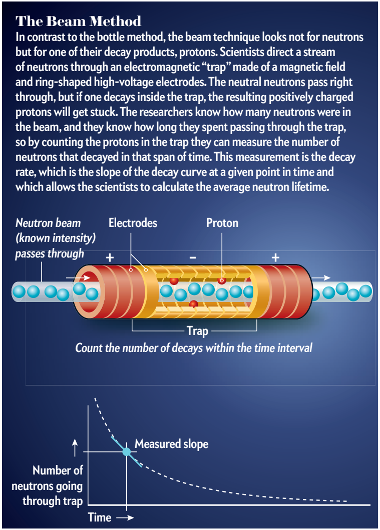
Two main types of experiments are under way: bottle traps count the number of neutrons that survive after various intervals, and beam experiments look for the particles into which neutrons decay.

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

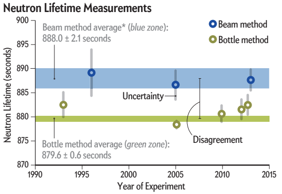
Illustration by Bill Mayer

Two methods to measure the neutron lifetime





Problems to meet ...



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

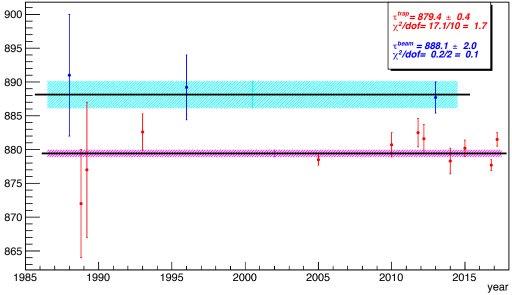
Why the neutron lifetime measured in UCN traps is smaller than that measured in beam method ? $n \to n'$ conversion can be plausible explanation: β-decay in invisible channel $n \to n' \to p' e' \bar{\nu}'$

Two methods to measure the neutron lifetime

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

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

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



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

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

Chapter I

Into the Darkness

The Neutron Dark Decay

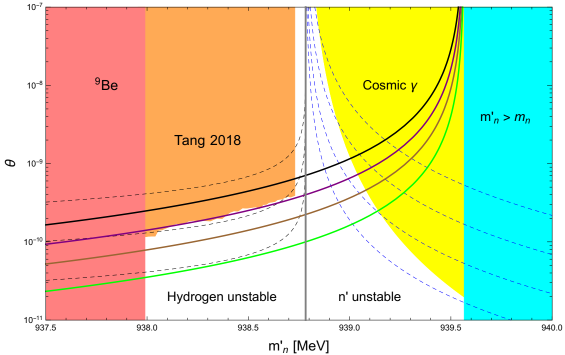
If this discrepancy is real (not due to some yet unknown systematics)

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

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

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

Status of the Neutron Dark Decay



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

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

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

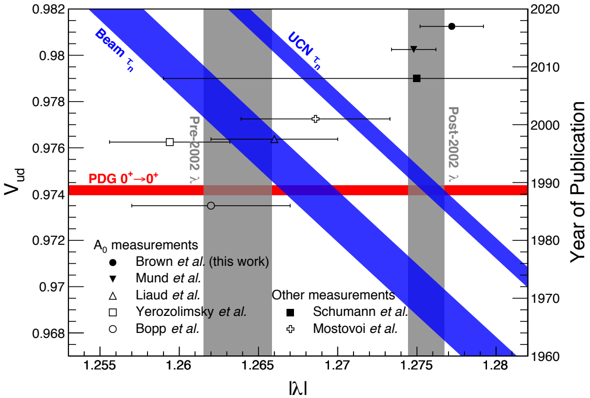
$m_{n'} < m_p + m_e$, Hydrogen atom decays $pe \to n'\nu_e$ $(\tau = 10^{20}, 10^{21}, 10^{22}$ yr)

Hydrogen Lifetime ?

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

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

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

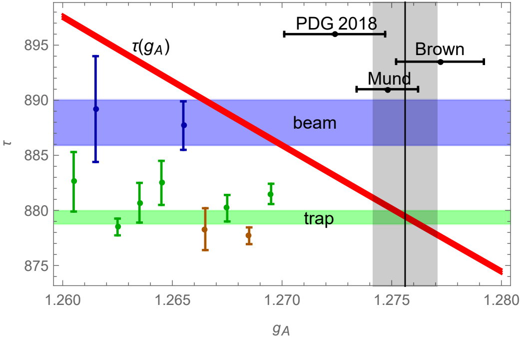


$|\lambda| = g_A$

$\tau_{\rm beam} = \tau_\beta$ seems incompatible with Standard Model

May indicate towards BSM physics? E.g. new contribution to β decay $n \to pe\bar{\nu}_e$? E.g. scalar form factor – mediated by exchange of charged Higgs (from extra Higgs doublet) – Does not help!

τ_n vs. β-asymmetry



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

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

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

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

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

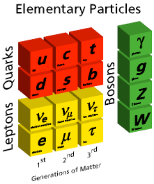
Chapter II

In and Out of the Darkness

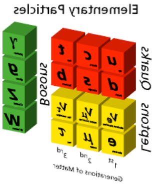
$SU(3) \times SU(2) \times U(1) \quad + \quad SU(3)' \times SU(2)' \times U(1)'$

$$G \times G'$$

Regular world



Mirror world



• Two identical gauge factors, e.g. $SU(5) \times SU(5)'$, with identical field contents and Lagrangians: $\mathcal{L}_{\rm tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\rm mix}$

• Exact parity $G \to G'$: no new parameters in dark Lagrangian $\mathcal{L}'$

• MM is dark (for us) and has the same gravity

• MM is identical to standard matter, (asymmetric/dissipative/atomic) but realized in somewhat different cosmological conditions: $T'/T \ll 1$.

• New interactions between O & M particles $\quad \mathcal{L}_{mix}$

Two parities

Fermions and anti-fermions :

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

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

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

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

Twin Fermions and anti-fermions :

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

B′=1/3 L′=1 B′=1/3 L′=1

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

B′=-1/3 L′=-1 B′=-1/3 L′=-1

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

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

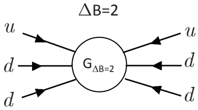
Mirror symmetry $(L, R \to R, L$ parity): $Y' = Y^* \qquad B - B' \to B - B'$

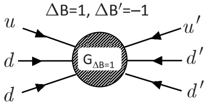
B violating operators between O and M particles in $\mathcal{L}_{\rm mix}$

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

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

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



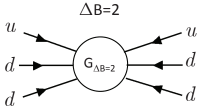


Oscillations $n(udd) \leftrightarrow \bar{n}(\bar{u}\bar{d}\bar{d})$ $(\Delta B = 2)$
$n(udd) \to \bar{n}'(\bar{u}'\bar{d}'\bar{d}'),\ n'(udd) \to \bar{n}(\bar{u}\bar{d}\bar{d})$ $(\Delta B = 1,\ \Delta B' = -1)$

Can co-generate Baryon asymmetries in both worlds
of the same sign, $B, B' > 0$, with $\Omega'_B \simeq 5\,\Omega_B$

Neutron– antineutron oscillation

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



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

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

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

Free neutron– antineutron oscillation

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

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

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

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

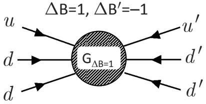
If $\omega_B t < 1$, then $P_{n\bar{n}}(t) = (t/\tau)^2 = (\varepsilon t)^2$

"Quasi-free" regime: for a given free flight time t, magnetic field should be properly suppressed to achieve $\omega_B t < 1$.
More suppression makes no sense !

Exp. Baldo-Ceolin et al, 1994 (ILL, Grenoble) : $t \simeq 0.1$ s, $\quad B < 100$ nT
$\tau > 2.7 \times 10^8 \quad \rightarrow \quad \varepsilon < 7.7 \times 10^{-24}$ eV
At ESS 2 orders of magnitude better sensitivity can be achieved, down to $\varepsilon \sim 10^{-25}$ eV

Neutron – mirror neutron mixing

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



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

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)

Even if $m_n = m_{n'}$, $n - \bar{n}'$ oscillation can be as fast as $\epsilon^{-1} = \tau_{n\bar{n}'} \sim 1$ s, without contradicting experimental and astrophysical limits.
(c.f. $\tau_{n\bar{n}} > 2.5 \times 10^8$ s for neutron – antineutron oscillation)

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

$n - n'$ mixing and transitional moments

$n - n'$ mass mixing $\epsilon \bar{n} n' + \mathrm{h.c.}$
Let us assume $\epsilon \sim 10^{-10}$ eV and $m_n - m_{n'} = \Delta m \sim 10^{-7}$ eV

transitional magn. moment/EDM $\mu_{nn'} (F_{\mu\nu} + F'_{\mu\nu}) \bar{n} \sigma^{\mu\nu} n' + \mathrm{h.c.}$

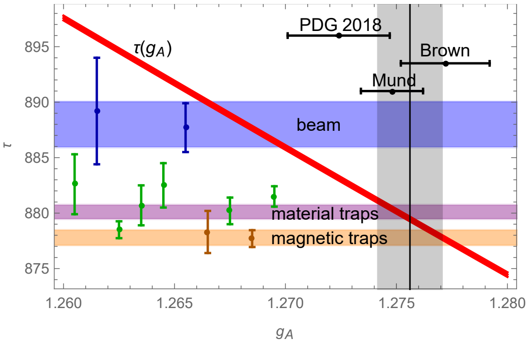
Hamiltonian of n and n' system becomes

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

If $B, B' \ll \Delta m$, oscillation probability is $P_{nn'} \simeq (\epsilon/\Delta m)^2 \sim 10^{-6}$
... Allowed by evaluation of UCN losses in traps

Interplay of ϵ, $\mu_{nn'}$ and $d_{nn'}$ can take place .... the latter is also interesting since in beam experiments also large electric fields are used

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



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

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

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

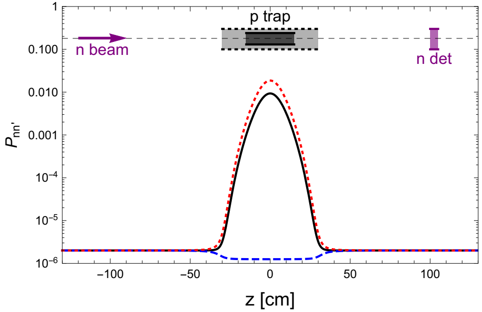
So experimentally we have $\quad \tau_{\rm magn} < \tau_{\rm mat} = \tau_n = \tau_\beta < \tau_{\rm beam}$

what s exactly predicted by my scenario So far so Good!

Beam Experiments

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

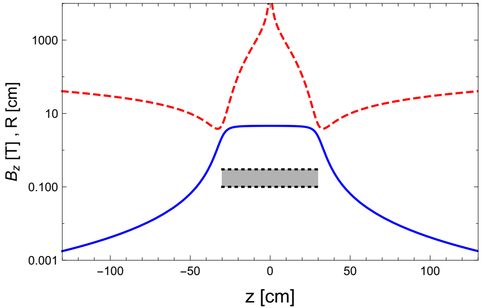
$N_n = P^{\rm tr}_{nn} L \int_A da \int dv\, I(v)/v$ and $N_{n'} = P^{\rm tr}_{nn'} L \int_A da \int dv\, I(v)/v$



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

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

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



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

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

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

If my hypothesis is correct, a simple solenoid with magnetic fields $\sim$ Tesla can be very effective machines that transform neutrons into dark matter.

Some groups in LANL, ORNL and NIST already think how to prepare simple experiments that could test this

Adiabatic conditions can be improved and 50 % transformation can be achieved

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

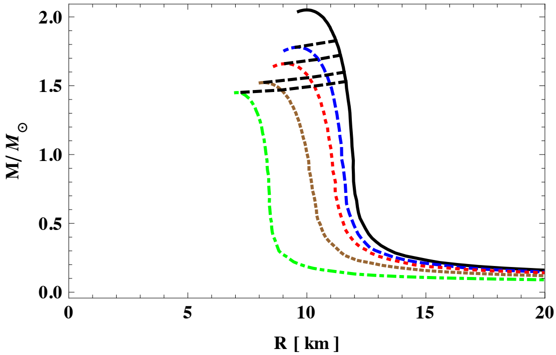
$R(z) = (d \ln B/dz)^{-1}$ – characterises the magnetic field gradient at the resonance

Neutron Stars

By $n \to n'$ conversion ordinary neutron star slowly transforms into mixed (50% - 50%) ordinary-mirror neutron star ....

O and M "neutrons" have same equation of state $p(n) = F[\rho(n)]$)

$\sqrt{2}$ rule: $R^{\rm mix}(M) = \frac{1}{\sqrt{2}} R^{\rm ord}(M), \quad M^{\rm mix}_{\rm max} = \frac{1}{\sqrt{2}} M^{\rm ord}_{\rm max},$



... solving "mixed" OV equations

Chapter III

Shining from the Darkness

Bright & Dark Sides of our Universe

Todays Universe: flat $\Omega_{\rm tot} \approx 1$ *(inflation)* ... and multi-component:

- $\Omega_B \simeq 0.05$ 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

B-genesis and DM require new physics: but which ? Why $\Omega_D/\Omega_B \sim 1$?

Visible matter from Baryogenesis *(Sakharov)*
B $(B-L)$ & CP violation, Out-of-Equilibrium
$\rho_B = m_B n_B$, $m_B \simeq 1$ 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.

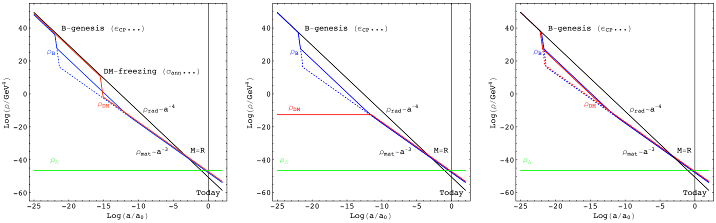
Dark matter: $\rho_D = m_X n_X$, but $m_X = ?$, $n_X = ?$
and why $m_X n_X = 5 m_B n_B$?

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

Axion	$m_a \sim$ meV	$n_a \sim 10^4 n_\gamma$	– CDM
Neutrinos	$m_\nu \sim$ eV	$n_\nu \sim n_\gamma$	– HDM $(\times)$
Sterile ν'	$m_{\nu'} \sim$ keV	$n_{\nu'} \sim 10^{-3} n_\nu$	– WDM
WIMP	$m_X \sim$ TeV	$n_X \sim 10^{-3} n_B$	– CDM
WimpZilla	$m_X \sim$ ZeV	$n_X \sim 10^{-12} n_B$	– CDM

How these Fine Tunings look ...

B-genesis + WIMP | B-genesis + axion | B-cogenesis



B-genesis + WIMP	B-genesis + axion	B-cogenesis
$m_X n_X \sim m_B n_B$	$m_a n_a \sim m_B n_B$	$m_{B'} n_{B'} \sim m_B n_B$
$m_X \sim 10^3 m_B$	$m_a \sim 10^{-13} m_B$	$m_{B'} \sim m_B$
$n_X \sim 10^{-3} n_B$	$n_a \sim 10^{13} n_B$	$n_{B'} \sim n_B$
Fine Tuning?	Fine Tuning?	Natural ?

Two different New Physics for B-genesis and DM ?
Or co-genesis by the same Physics explaining why $\Omega_{DM} \sim \Omega_B$?

Dark sector ... similar to our luminous sector?

"Imagination is more important than knowledge." *Albert*

For 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 !

If dark matter comes from extra gauge sector ... it is as *complex*:
$G' = SU(3)' \times SU(2)' \times U(1)'$? (+ 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 ?

Let us call it Yin-Yang Theory

in chinise, Yin-Yang means dark-bright duality

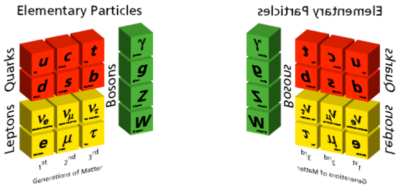
describes a philosophy how opposite forces are actually complementary, interconnected and interdependent in the natural world, and how they give rise to each other as they interrelate to one another.

$E_8 \times E'_8$

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

$$G \times G'$$

Regular world — Mirror world



- Two identical gauge factors, e.g. SM $\times$ SM$'$ or $SU(5) \times SU(5)'$, with identical field contents and Lagrangians: $\mathcal{L}_{\rm tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\rm mix}$
- M sector is dark (for us) and the gravity is a common force (between)
- Exact Z_2 parity $G \to G'$: no new parameter in dark Lagrangian $\mathcal{L}'$
- MM looks as non-standard DM but truly it as standard as our matter (self-interacting/dissipative/asymmetric/atomic)
- New interactions between O & M particles ($\mathcal{L}_{mix}$ – new parameters)
- Natural in string/brane theory: O & M matters localized on two parallel branes and gravity propagating in bulk: e.g. $E_8 \times E_8'$

– 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 M World is OK if : Z.B., Comelli, Villante, 2001

(A) after inflation M world was born colder than O world

(B) all particle interactions between M and O sectors are so feeble that cannot bring them into equilibrium in later epochs

(C) two systems evolve adiabatically when the universe expands (no entropy production) and their temperature ratio T'/T remains nearly constant.

If $x = T'/T \ll 1$, BBN is OK

M world in Winter

Z.B., Comelli, Villante, 2000

$T'/T < 0.5$ is enough to concord with the BBN limits and do not affect standard primordial mass fractions: 75% H + 25% ^{4}He.
(Cosmological limits are more severe, requiring $T'/T < 0.2$ os so.)
In turn, for M world this implies helium domination: 25% H$'$ + 75% ^{4}He$'$.

Because of $T' < T$, in mirror photons decouple much earlier than ordinary photons, and after that M matter behaves for the structure formation and CMB anisotropies essentially as CDM. This concords M matter with WMAP/Planck, BAO, Ly-α etc. if $T'/T < 0.25$ or so.

Halo problem – if $\Omega'_B \simeq \Omega_B$, M matter makes ~ 20 % of DM, forming dark disk, while ~ 80 % may come from other type of CDM (WIMP?)
But perhaps 100 % ? if $\Omega'_B \simeq 5\Omega_B$: – M world is helium dominated, and the star formation and evolution can be much faster. Halos could be viewed as mirror elliptical galaxies, with our matter inside forming disks.

Because of $T' < T$, the situation $\Omega'_B > \Omega_B$ becomes plausible in baryogenesis. So, M matter can be dark matter (as we show below)

Experimental and observational manifestations of mirror matter

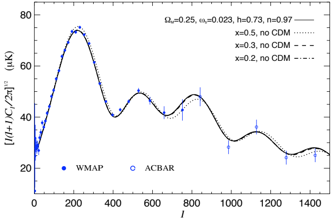
A. *Cosmological implications.* $T'/T < 0.2$ or so, $\Omega'_B/\Omega_B = 1 \div 5$.
Mass fraction: H' – 25%, He' – 75%, and few % of heavier C', N', O' etc.

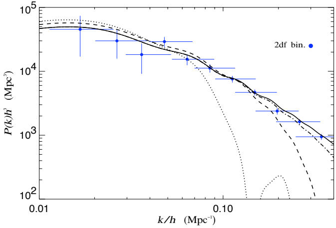
- Mirror baryons as asymmetric/collisional/dissipative/atomic dark matter: M hydrogen recombination and M baryon acoustic oscillations?
- Easier formation and faster evolution of stars: Dark matter disk? Galaxy halo as mirror elliptical galaxy? Microlensing ? Neutron stars? Black Holes? Binary Black Holes? Central Black Holes?

B. *Direct detection.* M matter can interact with ordinary matter e.g. via kinetic mixing $\epsilon F^{\mu\nu}F'_{\mu\nu}$, etc. Mirror helium as most abundant mirror matter particles (the region of DM masses below 5 GeV is practically unexplored). Possible signals from heavier nuclei C,N,O etc.

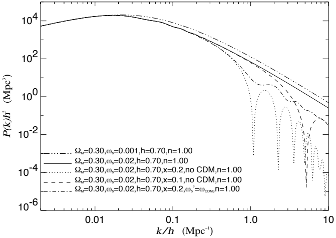
C. *Oscillation phenomena between ordinary and mirror particles.*
The most interesting interaction terms in $\mathcal{L}_{\rm mix}$ are the ones which violate B and L of both sectors. Neutral particles, elementary (as e.g. neutrino) or composite (as the neutron or hydrogen atom) can mix with their mass 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 $\Omega'_B/\Omega_B = 1 \div 5$.

CMB and LSS power spectra





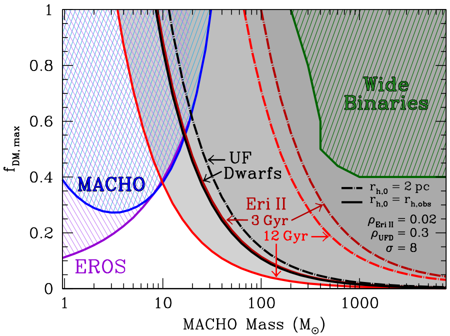
Z.B., Ciarcelluti, Comelli, Villante, 2003



Acoustic oscillations and Silk damping at short scales: $x = T'/T < 0.2$

Can Mirror stars be progenitors of gravitational Wave bursts GW150914 etc. ?

Picture of Galactic halos as mirror ellipticals (Einasto density profile), O matter disk inside (M stars = Machos).
Microlensing limits: $f \sim 20-40$ % for $M = 1-10\ M_\odot$,
$f \sim 100$ % is allowed for $M = 20-200\ M_\odot$ but see Brandt '05



GW events without any optical counterpart

point towards massive BH compact binaries, $M \sim 10-30\ M_\odot$ and radius $R \sim 10 R_\odot$

How such objects can be formed ?

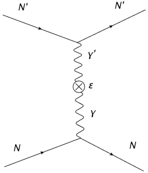
M matter: 25 % Hydrogen vs 75 % Helium: M stars more compact, less opaque, less mass loses by stellar wind and evolving much faster.
Appropriate for forming such BH binaries ?

Discussing $\mathcal{L}_{\rm mix}$: possible portal between O and M particles

- Photon-mirror photon kinetic mixing $\epsilon F^{\mu\nu} F'_{\mu\nu}$

Experimental limit $\epsilon < 4 \times 10^{-7}$
Cosmological limit $\epsilon < 5 \times 10^{-9}$

Makes mirror matter nanocharged ($q \sim \epsilon$)
A promising portal for DM direct detection Foot, 2003

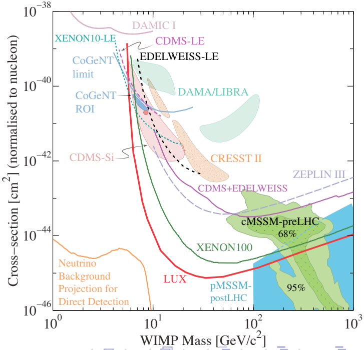


Mirror atoms: He' – 75 %, C',N',O' etc. few %
Rutherford-like scattering

$$\frac{d\sigma_{AA'}}{d\Omega} = \frac{(\epsilon\alpha Z Z')^2}{4\mu^2_{AA'} v^4 \sin^4(\theta/2)}$$

or

$$\frac{d\sigma_{AA'}}{dE_R} = \frac{2\pi(\epsilon\alpha Z Z')^2}{M_A v^2 E_R^2}$$



OM-MM interactions in the Early Universe after recombination

After recombination fractions $\sim 10^{-4}$ of OM and $\sim 10^{-3}$ of MM remains ionized. $\gamma - \gamma'$ kinetic mixing $\rightarrow$ Rutherford scatterings $ep' \rightarrow ep'$, $ee' \rightarrow ee'$ etc

Relative motion (rotation) of O and M matter drags electrons but not protons/ions which are much heavier. So circular electric currents emerge which can generate magnetic field. MHD equations with the source (drag) term induces magnetic seeds $B, B' \sim 10^{-15}$ G in galaxies/clusters then amplified by dynamo. So magnetic fields $\sim \mu$G can be formed in very young galaxies Z.B., Dolgov, Tkachev, 2013

MM capture by Earth can induce mirror magnetic field in the Earth, even bigger than ordinary 0.5 G.

New EDGES measurements of 21 cm emission (T-S hydrogen) indicates that at redshift $z \sim 17$ baryons were factor 2 cooler than predicted: if true, it can be beautiful implication of OM matter cooling (momentum transfer) via their Rutherford collisions with (cooler) MM

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

Two parities

Fermions and anti-fermions :

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

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

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

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

Twin Fermions and anti-fermions :

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

B′=1/3 L′=1 B′=1/3 L′=1

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

B′=-1/3 L′=-1 B′=-1/3 L′=-1

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

$$(\bar{u}'_L Y'_u q'_L \bar{\phi}' + \bar{d}'_L Y'_d q'_L \phi' + \bar{e}'_L Y'_e l'_L \phi') + (u'_R Y'^*_u \bar{q}'_R \phi' + d'_R Y'^*_d \bar{q}'_R \bar{\phi}' + e'_R Y'^*_e \bar{l}'_R \bar{\phi}')$$

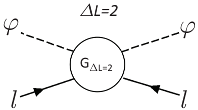
Z_2 symmetry $(L, R \to L, R)$: $\quad Y' = Y \quad B - B' \to -(B - B')$

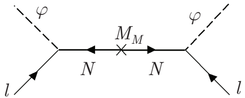
PZ_2 symmetry $(L, R \to R, L)$: $\quad Y' = Y^* \quad B - B' \to B - B'$

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

- $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$ $(\Delta L = 2)$ – neutrino (seesaw) masses $m_\nu \sim v^2/M$

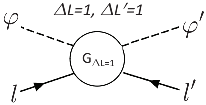
M is the (seesaw) scale of new physics beyond EW scale.





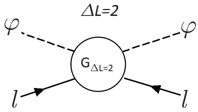
- Neutrino -mirror neutrino mixing – (active - sterile mixing)

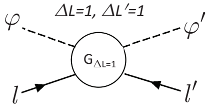
L and L' violation: $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$, $\frac{1}{M}(l'\bar{\phi}')(l'\bar{\phi}')$ and $\frac{1}{M}(l\bar{\phi})(l'\bar{\phi}')$



Mirror neutrinos are natural candidates for sterile neutrinos

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





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

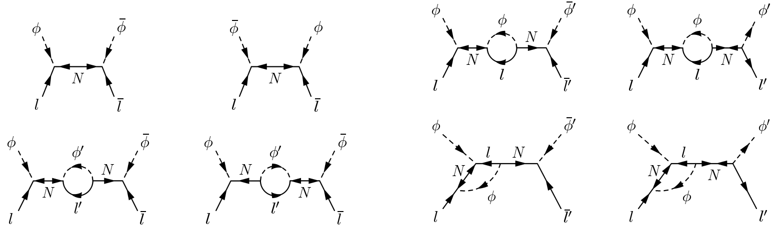
- These processes should be out-of-equilibrium
- Violate baryon numbers in both worlds, $B - L$ and $B' - L'$
- Violate also CP, given complex couplings

Green light to celebrated conditions of Sakharov

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

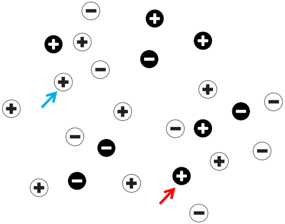


Complex Yukawa couplings $Y_{ij}l_iN_j\bar{\phi} + Y'_{ij}l'_iN_j\bar{\phi}' + \mathrm{h.c.}$

Xerox symmetry $\rightarrow Y' = Y$, Mirror symmetry $\rightarrow Y' = Y^*$

Co-leptogenesis: Mirror Matter as hidden 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 (LR): $Y' = Y^* \quad \to \quad \Delta\sigma' = -\Delta\sigma \quad \to \quad B, B' > 0$

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

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

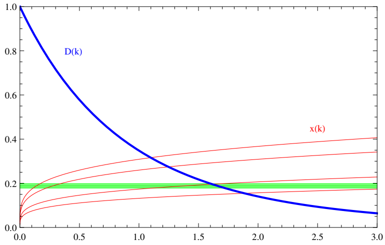
$$\Omega'_B = \Omega_B \simeq 10^3 \frac{JM_{Pl}T_R^3}{M^4} \simeq 10^3 J \left(\frac{T_R}{10^{11}\ {\rm GeV}}\right)^3 \left(\frac{10^{13}\ {\rm GeV}}{M}\right)^4$$

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:



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

Free Energy from DM for the future generations ?

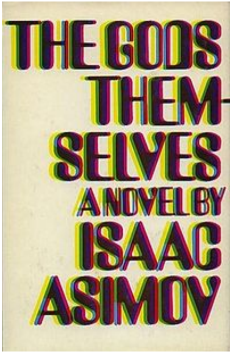
$n' \to \bar{n}$ produces our antimatter from mirror DM

Encounter of matter and antimatter leads to immediate (uncontrollable) annihilation which can be destructive

Annihilation can take place also between our matter and dark matter, but controllable by tuning of vacuum and magnetic conditions. Dark neutrons can be transformed into our antineutrons ....

Two civilisations can agree to built scientific reactors and exchange neutrons ... and turn the energy produced by each reactor in 1000 times more energy for parallel world .. and all live happy and healthy ...

Isaak Asimov



First Part: Against Stupidity ...

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

Third Part: ... Contend in Vain?

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

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

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

Appendices

The Mass Mixing $\epsilon(nCn' + \mathrm{h.c.})$ comes from six-fermions effective operator $\frac{1}{M^5}(udd)(u'd'd')$, M is the scale of new physics violating B and B' – but conserving $B - B'$

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

Key observation: *$n - n'$ oscillation cannot destabilise nuclei: $(A, Z) \to (A-1, Z) + n'(p'e'\bar{\nu}')$ forbidden by energy conservation*

Surprisingly, $n - \bar{n}'$ oscillation can be as fast as $\epsilon^{-1} = \tau_{nn'} \sim 1$ s, without contradicting any experimental and astrophysical limits. (c.f. $\tau_{n\bar{n}} > 2.5 \times 10^8$ s for neutron – antineutron oscillation)
Disappearance $n \to \bar{n}'$ (regeneration $n \to \bar{n}' \to n$) can be searched at small scale 'Table Top' experiments

Neutron – mirror neutron oscillation probability

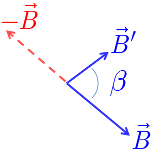
$$H = \begin{pmatrix} m_n + \mu_n \mathbf{B}\sigma & \epsilon \\ \epsilon & m_n + \mu_n \mathbf{B}'\sigma \end{pmatrix}$$

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

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

Experimental limits on $n - n'$ oscillation time