Neutron Oscillations:
What, Which, Why, Where, When and How ?

Zurab Berezhiani

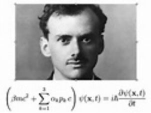
University of L'Aquila and LNGS

Pisa, 9 March 2017

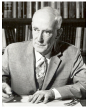
Contents

Some epochal discoveries after 30's of XIX ...

Anti-matter, 1931-32




Dark matter , 1932-33

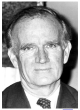



Neutron, 1932-33



Parity Violation, 1956-57


CP Violation, 1964

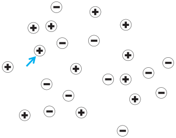



...and a prophetic idea on the origin of matter

Baryon Violation, 1966

Matter (Baryon asymmetry) in the early universe can be originated (from zero) by processes that

- Violate B (better $B - L$)
- Violate CP
- and go out-of-equilibrium at some early epoch



I want to pose a question in this way:
Can the issues of the antimatter, dark matter, neutron, parity, CP-violation, baryon violation and some other issues of Standard Model more intimately related ?

Standard Model on T-shirts

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ i \bar{\psi} \not{D} \psi + h.c.$$
$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$
$$+ |D_\mu \phi|^2 - V(\phi)$$

Fermions (= matter): quarks and leptons, *3 generations*

Bosons (= interactions): gauge fields + God's particle – Higgs

Standard Model vs. P, C, T and B & L

Fermions:

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

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

Anti-Fermions:

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

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

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm Gauge} + \mathcal{L}_{\rm Higgs} + \mathcal{L}_{\rm Yuk}$$

CPT is OK (Local Lagrangian)

$P\ (\Psi_L \to \Psi_R)$ & $C\ (\Psi_L \to \bar{\Psi}_L)$ broken by gauge interactions

$CP\ (\Psi_L \to \bar{\Psi}_R)$ broken by complex Yukawas $Y = Y_{ij}^{u,d,e}$

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

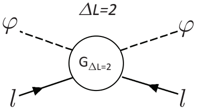
There are no renormalizable interactions which can break B and L !

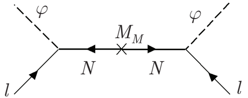
Good for our stability, Bad for baryogenesis

Baryogenesis requires new physics:

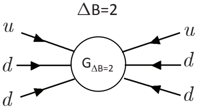
B & L can be violated only in higher order (non-renormalizable) terms

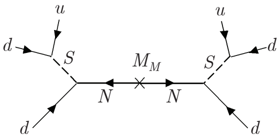
- $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$ $(\Delta L = 2)$ – neutrino (seesaw) masses $m_\nu \sim v^2/M$





- $\frac{1}{M^5}(udd)(udd)$ $(\Delta B = 2)$ – neutron-antineutron oscillation $n \to \bar{n}$

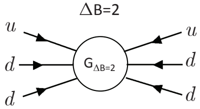




can originate from new physics related to scale $M \gg v_{\rm EW}$ via seesaw

Neutron– antineutron oscillation Kuzmin 1970

The Mass Mixing $\epsilon(n^T C n + \bar{n}^T C \bar{n})$ (Majorana mass of neutron)
violating B by two units comes from six-fermions effective operator $\frac{1}{M^5}(udd)(u'd'd')$, M is the scale of new physics



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

free $n - \bar{n}$ oscillation time $\tau = \epsilon^{-1}$

Key observation: *$n - \bar{n}$ 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

$\epsilon < 1.2 \times 10^{-24}$ eV $\to$ $\tau > 1.3 \times 10^8$ s Fe, Soudan 2002

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

Neutron– antineutron oscillation   Kuzmin 1970

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

Oscillation probability $P_{n\bar{n}}(t) = \frac{\epsilon^2}{\epsilon^2+\omega_B^2} \sin^2 \left(t\sqrt{\epsilon^2 + \omega_B^2} \right)$ where $\omega_B = \mu_n B$

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

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

"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, $B < 100$ nT
$\tau > 2.7 \times 10^8 \quad \rightarrow \quad \epsilon < 7.7 \times 10^{-24}$ eV

but at ESS 2 orders of magnitude better sensitivity can be achieved, down to $\epsilon \sim 10^{-25}$ eV

Dark matter requires new physics

Standard Model has no candidate for dark matter

massive neutrino ($\sim$ 20 eV) was a natural "standard" candidate of "hot" dark matter (HDM) forming cosmological structures (Pencakes) – but it was excluded by astrophysical observations in 80's, and later on by the neutrino experiments! – **RIP**

In about the same period the BBN limits excluded dark matter in the form of invisible baryons (dim stars, etc.) – **RIP**

Then a new *Strada Maestra* was opened – $\mathcal{SUSY}$
– well-motivated theoretical concept promising to be a highway for solving many fundamental problems, brought a natural and *almost "Standard"* candidate WIMP – **undead, but looks useless**

Another well-motivated candidate, Axion, emerged from Peccei-Quinn symmetry for solving strong CP problem – **alive, but seems confused**

All other candidates in the literature are *ad hoc !*

Apart one exception –
which may answer to tantalizing question: do baryogenesis and dark matter require two different new physics, or just one can be enough?

Cosmic Concordance and Dark Side of the Universe

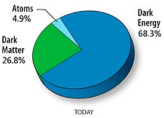
Todays Universe: flat $\Omega_{\rm tot} \approx 1$ *(inflation)* and multi-component:

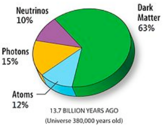
- $\Omega_B \simeq 0.05$ observable matter: electron, proton, neutron
- $\Omega_D \simeq 0.25$ dark matter: WIMP? axion? sterile ν? ...
- $\Omega_\Lambda \simeq 0.70$ dark energy: Λ-term? Quintessence? ....

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, Affleck-Dine, EW B ...)

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

Different physics for B-genesis and DM?
Or co-genesis by the same Physics ?

Why $\Omega_D/\Omega_B \sim 1$? Or why $m_B \rho_B \sim m_X \rho_X$?

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.

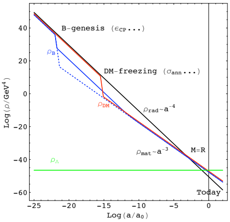
Dark matter: $\rho_D = m_X n_X$, but $m_X = ?$, $n_X = ?$
n_X is model dependent: DM particle mass and interaction strength (production and annihilation cross sections), freezing conditions, etc.

- Axion
- Neutrinos
- Sterile ν'
- WIMP
- WimpZilla
- Para-baryons

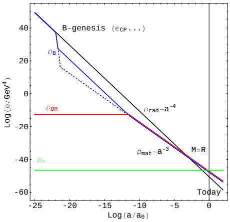
- $m_a \sim 10^{-5}$ eV $n_a \sim 10^4 n_\gamma$ - CDM
- $m_\nu \sim 10^{-1}$ eV $n_\nu \sim n_\gamma$ - HDM $(\times)$
- $m_{\nu'} \sim 10$ keV $n_{\nu'} \sim 10^{-3} n_\nu$ - WDM
- $m_X \sim 1$ TeV $n_X \sim 10^{-3} n_B$ - CDM
- $m_X \sim 10^{14}$ GeV $n_X \sim 10^{-14} n_B$ - CDM
- $m_{B'} \simeq 1$ GeV $n_{B'} \sim n_B$ - A-SI-D-A-DM

How these Fine Tunings look ...

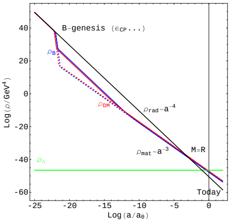
B-genesis + WIMP



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 $\Omega_{DM} \sim \Omega_B$?

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-conserviolation, 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'-conserviolation, 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

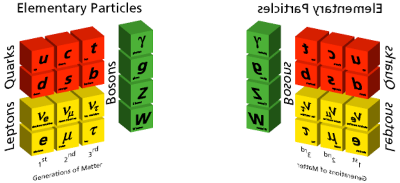
describes a philosophy how opposite forces are actually complementary, interconnected and interdependent in the natural world, and how they give rise to each other as they interrelate to one another.

$E_8 \times E'_8$

$SU(3) \times SU(2) \times U(1)$ & $SU(3)' \times SU(2)' \times U(1)'$

$$G \times G'$$

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 $\mathcal{L}'$
- M sector is dark (for us) and the gravity is a common force (with us)
- M matter looks as non-standard for dark matter but it is truly standard in direct sense, just as our matter (self-interacting/dissipative/asymmetric)
- New interactions are possible between O & M particles $\mathcal{L}_{mix}$
- Natural in string/brane theory: O & M matters localized on two parallel branes and gravity propagating in bulk: e.g. $E_8 \times E_8'$

$SU(3)\times SU(2)\times U(1)$ 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

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

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

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

Experimental and observational manifestations

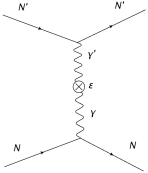
A. *Cosmological implications.* $T'/T < 0.2$ or so, $\Omega'_B/\Omega_B = 1 \div 5$.
Mass fraction: H' – 25%, He' – 75%, and few % of heavier C', N', O' etc.
• Mirror baryons as asymmetric/collisional/dissipative/atomic dark matter: M hydrogen recombination and M baryon acoustic oscillations?
• Easier 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 $\Omega'_B/\Omega_B = 1 \div 5$.

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 $\epsilon < 5 \times 10^{-9}$

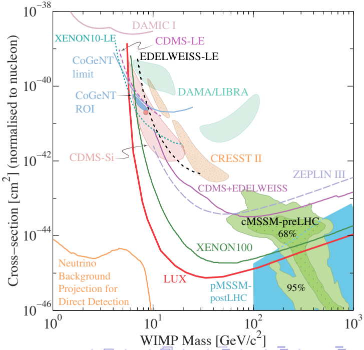
Makes mirror matter nanocharged ($q \sim \epsilon$)
A promising portal for DM direct detection Foot, 2003

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

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

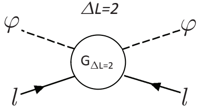
or

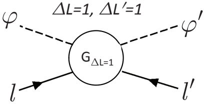
$$\frac{d\sigma_{AA'}}{dE_R} = \frac{2\pi(\epsilon\alpha Z Z')^2}{M_A v^2 E_R^2}$$



L and B violating operators between O and M particles

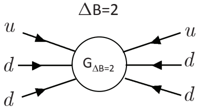
• Neutrino -mirror neutrino mixing – (active - sterile mixing)
L and L' violation: $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$, $\frac{1}{M}(l'\bar{\phi}')(l'\bar{\phi}')$ and $\frac{1}{M}(l\bar{\phi})(l'\bar{\phi}')$

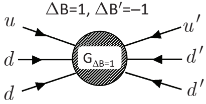




M is the (seesaw) scale of new physics beyond EW scale.
Mirror neutrinos are most natural candidates for sterile neutrinos

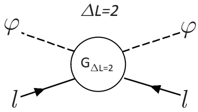
• Neutron -mirror neutron mixing – (Active - sterile neutrons) B and B' violating operators: $\frac{1}{M^5}(udd)(udd)$ and $\frac{1}{M^5}(udd)(u'd'd')$

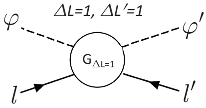




Neutron Oscillations:
What, Which, Why, Where, When and How ?
Zurab Berezhiani
Summary
Dark Matter Enigma
Mirror Matter
Neutron–mirror neutron oscillation
The neutron lifetime enigma
Conclusions

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 $l\phi \to \bar{l}'\bar{\phi}'$ $(\Delta L = 1,\, \Delta L' = 1)$





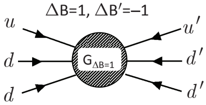
After inflation, our world is heated and mirror world is empty: but ordinary particle scatterings transform them into mirror particles, heating also mirror world.

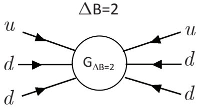
- These processes should be out-of-equilibrium
- Violate baryon numbers in both worlds, $B - L$ and $B' - L'$
- Violate also CP, given complex couplings

Green light to celebrated conditions of Sakharov

The interactions able to make such cogenesis, should also lead to mixing of our neutral particles into their mass degenerate mirror twins.

The Mass Mixing $\epsilon(\bar{n}n' + \bar{n}'n)$ 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 $B - B'$





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

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

Surprisingly, $n - n'$ 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) Oscillations $n \to n'$ (regeneration $n \to n' \to n$) can be searched at small scale 'Table Top' experiments

Neutron – mirror neutron oscillation

PRL **96,** 081801 (2006) PHYSICAL REVIEW LETTERS week ending 3 MARCH 20

Neutron–Mirror-Neutron Oscillations: How Fast Might They Be?

Zurab Berezhiani[1,*] and Luís Bento[2,†]

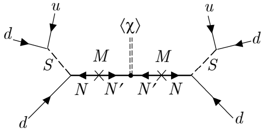
[1]*Dipartimento di Fisica, Università di L'Aquila, I-67010 Coppito, AQ, Italy and Laboratori Nazionali del Gran Sasso, INFN, I-67010 Assergi, AQ, Italy*

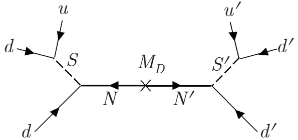
[2]*Faculdade de Ciências, Centro de Física Nuclear da Universidade de Lisboa, Universidade de Lisboa, Avenida Professor Gama Pinto 2, 1649-003 Lisboa, Portugal*

(Received 12 August 2005; published 27 February 2006)

We discuss the phenomenological implications of the neutron (n) oscillation into the mirror neutron (n'), a hypothetical particle exactly degenerate in mass with the neutron but sterile to normal matter. We show that the present experimental data allow a maximal n-n' oscillation in vacuum with a characteristic time τ much shorter than the neutron lifetime, in fact as small as 1 sec. This phenomenon may manifest in neutron disappearance and regeneration experiments perfectly accessible to present experimental capabilities and may also have interesting astrophysical consequences, in particular, for the propagation of ultra high energy cosmic rays.

Seesaw between ordinary and mirror neutrons





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

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

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

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

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

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

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

Neutron – mirror neutron oscillation probability

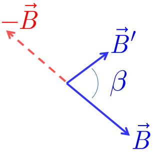
$$H = \begin{pmatrix} m_n + \mu_n \mathbf{B}\sigma & \epsilon \\ \epsilon & m_n + \mu_n \mathbf{B}'\sigma \end{pmatrix}$$

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

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

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

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

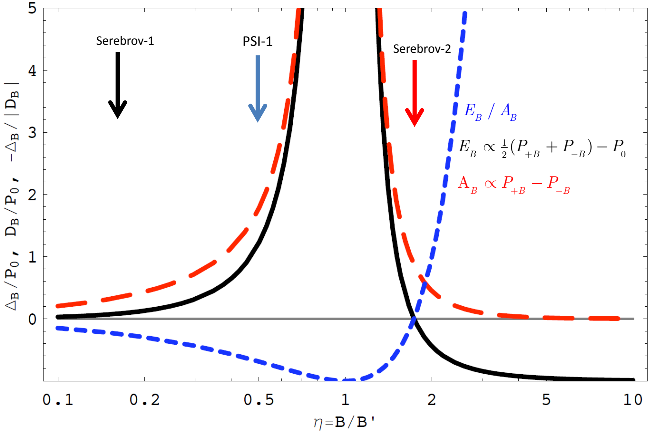


where $\omega = \frac{1}{2}\left|\mu B\right|$ and $\omega' = \frac{1}{2}\left|\mu B'\right|$; τ - oscillation time

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

A and E are expected to depend on magnetic field

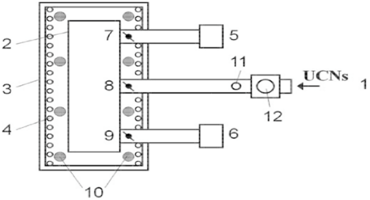
E.g. assume B'=0.12 Gauss



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.

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

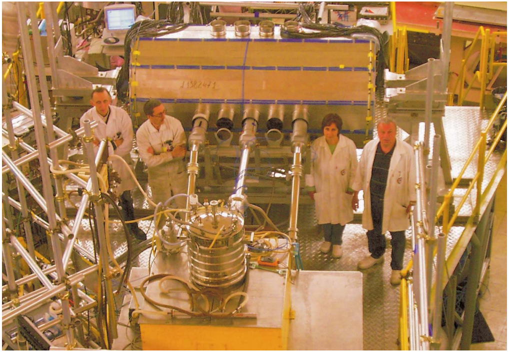
$$\frac{N_{B1}(T_S)}{N_{B2}(T_S)} = \exp\left[\left(\bar{\mathcal{P}}_{B2} - \bar{\mathcal{P}}_{B1}\right)\nu T_S\right]$$

So if we find that:

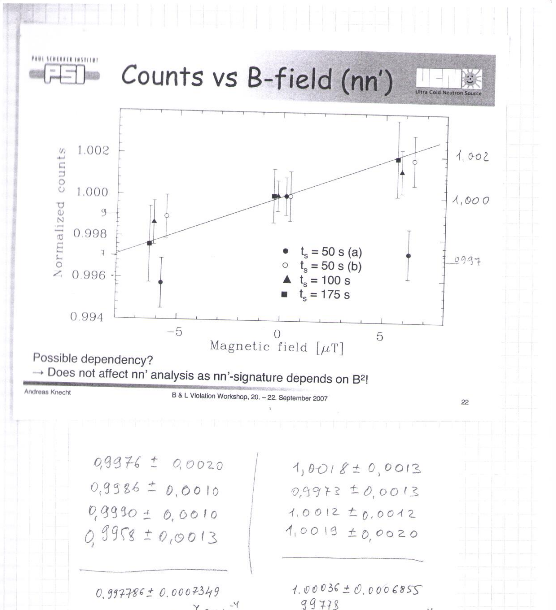
$$A(B, T_S) = \frac{N_B(T_S) - N_{-B}(T_S)}{N_B(T_S) + N_{-B}(T_S)} \neq 0 \qquad E(B, b, T_S) = \frac{N_B(T_S)}{N_b(T_S)} - 1 \neq 0$$

Experiments

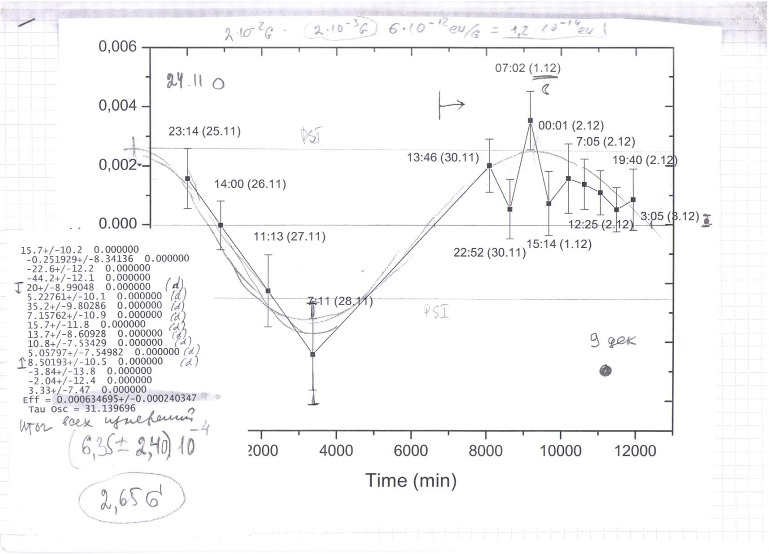
Several experiment were done, 3 by PSI group, most sensitive by the Serebrov's group at ILL, with 190 l beryllium plated trap for UCN



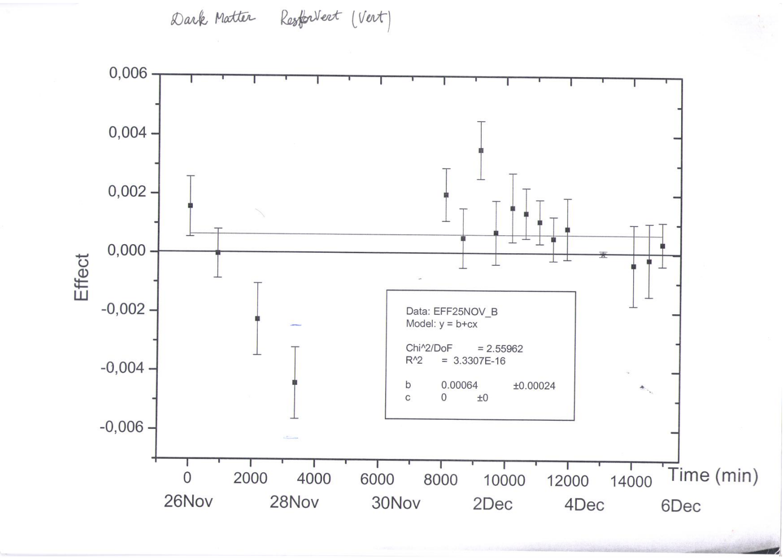
Serebrov – Cheking PSI Anomaly



Serebrov experiment III – 1st Fax



Serebrov experiment III – 2nd Fax



Neutron – mirror neutron oscillation

Eur. Phys. J. C (2012) 72:1974
DOI 10.1140/epjc/s10052-012-1974-5

THE EUROPEAN PHYSICAL JOURNAL C

Letter

Magnetic anomaly in UCN trapping: signal for neutron oscillations to parallel world?

Zurab Berezhiani[1,2,a], **Fabrizio Nesti**[1]

[1]Dipartimento di Fisica, Università dell'Aquila, Via Vetoio, 67100 Coppito, L'Aquila, Italy
[2]INFN, Laboratori Nazionali Gran Sasso, 67010 Assergi, L'Aquila, Italy

Received: 2 March 2012 / Published online: 11 April 2012

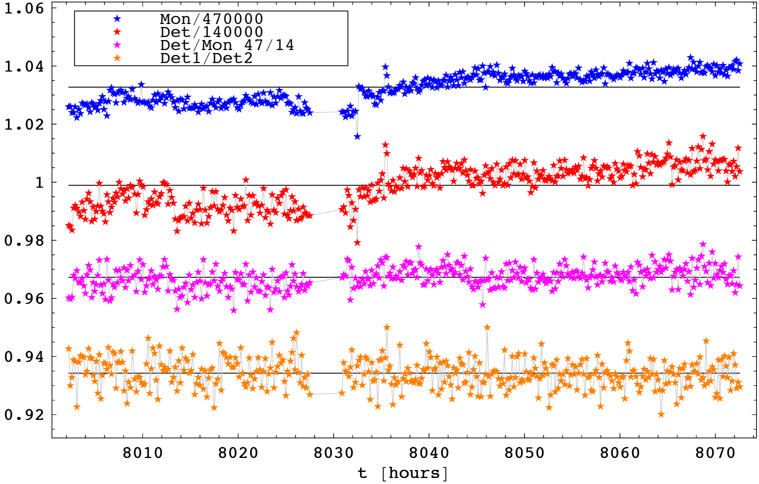
Abstract Present experiments do not exclude that the neutron n oscillates, with an appreciable probability, into its invisible degenerate twin from a parallel world, the so-called mirror neutron n'. These oscillations were searched experimentally by monitoring the neutron losses in ultra-cold neutron traps, where they can be revealed by the magnetic field dependence of n–n' transition probability. In this work we reanalyze the experimental data acquired by the group of A.P. Serebrov at Institute Laue–Langevin, and find a dependence at more than 5σ away from the null hypothesis. This anomaly can be interpreted as oscillation of neutrons to mirror neutrons with a timescale of few seconds, in the presence of a mirror magnetic field order 0.1 G at the Earth. This result, if confirmed by future experiments, will have deepest consequences for fundamental particle physics, astrophysics and cosmology.

Parallel matter can be a viable candidate for dark matter [7–9]. Certain $B-L$ and CP violating processes between ordinary and mirror particles can generate the baryon asymmetries in both sectors [10–12] which scenario can naturally explain the relation $\Omega_D/\Omega_B \simeq 5$ between the dark and visible matter fractions in the Universe [13–16]. Such interactions can be mediated by heavy messengers coupled to both sectors, as right-handed neutrinos [10–12] or extra gauge bosons/gauginos [17].[1] In the context of extra dimensions, ordinary and mirror sectors can be modeled as two parallel three-dimensional branes and particle processes between them mediated by the bulk modes or "baby branes" can be envisaged [24].

On the other hand, these interactions can induce mixing phenomena between ordinary and mirror particles. In fact, any *neutral* particle, *elementary or composite*, may oscillate

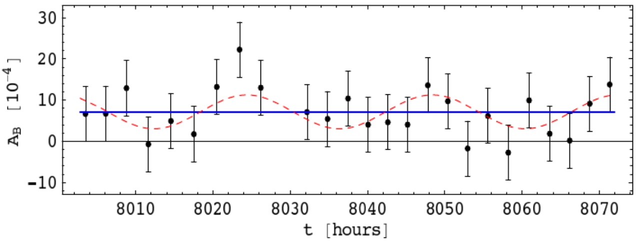
Serebrov III – Drifts of detector and monitor counts

Exp. sequence: $\{B_-, B_+, B_+, B_-, B_+, B_-, B_-, B_+\}$, $B = 0.2$ G



Serebrov III – magnetic field vertical

Exp. sequence: $\{B_-, B_+, B_+, B_-, B_+, B_-, B_-, B_+\}$, $B = 0.2$ G



Analysis pointed out the presence of a signal:

$$A(B) = (7.0 \pm 1.3) \times 10^{-4} \qquad \chi^2_{/dof} = 0.9 \longrightarrow 5.2\sigma$$

interpretable by $n \to n'$ with $\tau_{nn'} \sim 2 - 10s$' and $B' \sim 0.1G$

Z.B. and Nesti, 2012

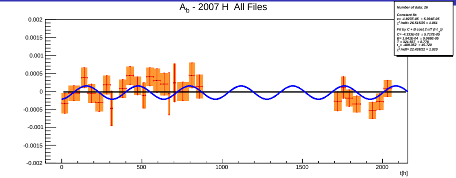
Earth mirror magnetic field via the electron drag mechanism

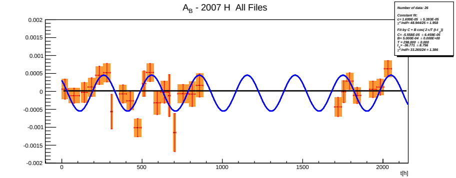
Earth can accumulate some, even tiny amount of mirror matter due to Rutherford-like scattering of mirror matter due to photon-mirror photon kinetic mixing.
Rotation of the Earth drags mirror electrons but not mirror protons (ions) since the latter are much heavier.
Circular electric currents emerge which 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.

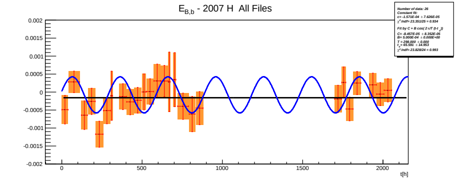
Such mechanism can also induce cosmological magnetic fields
Z.B., Dolgov, Tkachev, 2013

Serebrov II – magnetic field Horizontal

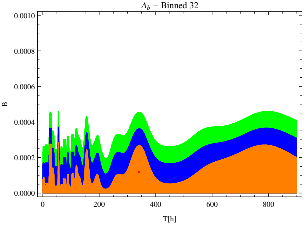
$$\{b_-, B_-, B_+, b_+, b_+, B_+, B_-, b_-\}\ ,\ B = 0.2\ \text{G}\ ,\ b < 10^{-3}\ \text{G}$$

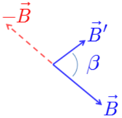


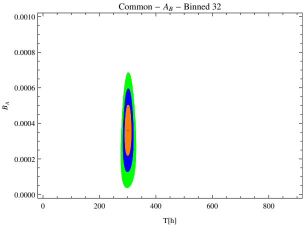


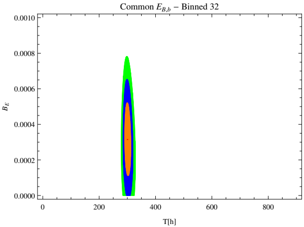


Serebrov 2007 – magnetic field Horizontal

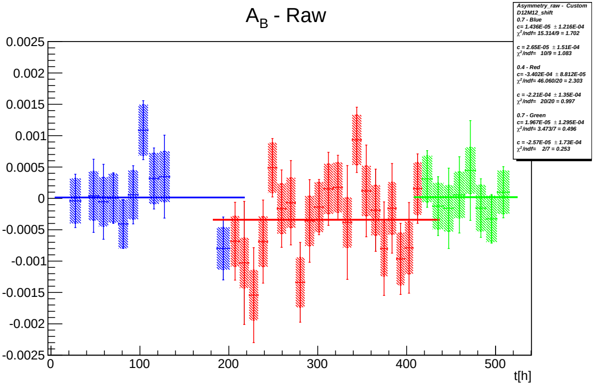




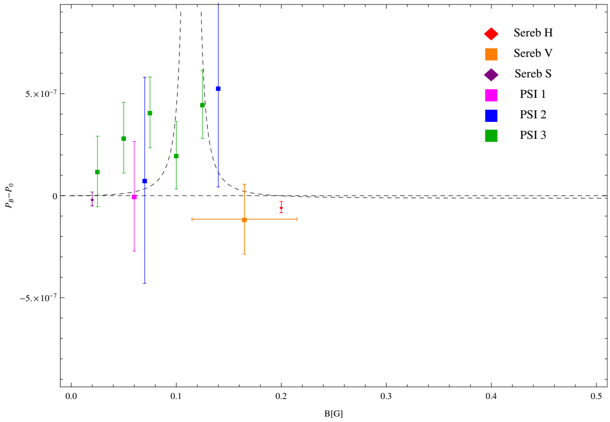




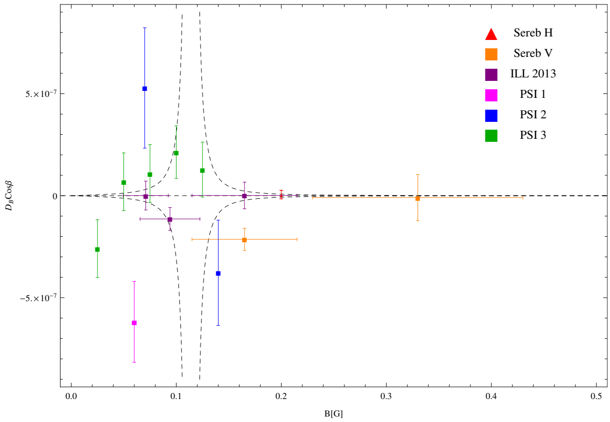
My own neasurements 2014 at ILL – with Biondi, Geltenbort et al.



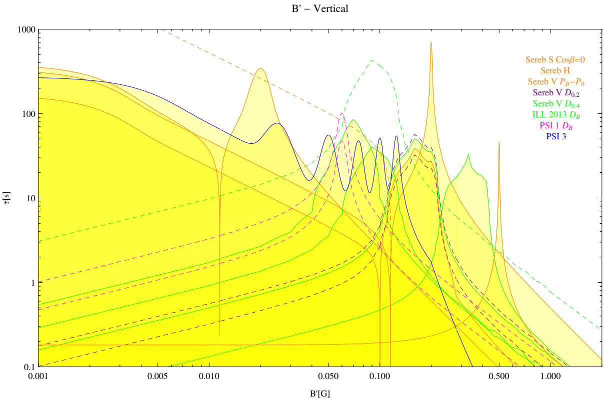
All Mesaurements – values for $P_B - P_0$



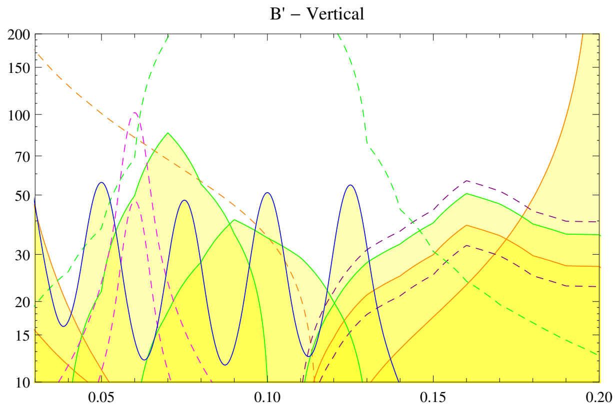
All Mesaurements – values for $P_{-B} - P_{+B}$



All Mesaurements – All Results



All Mesaurements – All Results



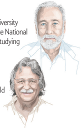
The neutron enigma ...

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

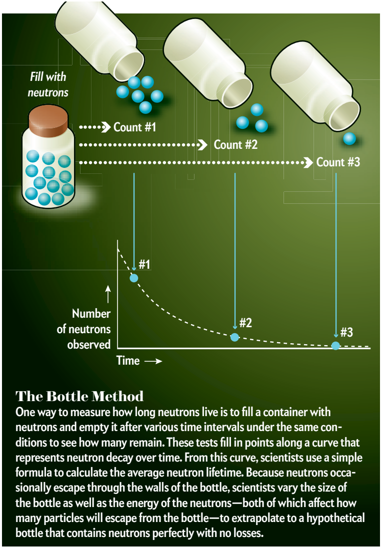
The best experiments in the world cannot agree on how long neutrons live before decaying into other particles.

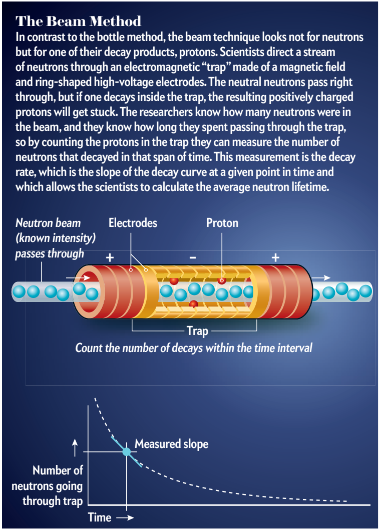
Two main types of experiments are under way: bottle traps count the number of neutrons that survive after various intervals, and beam experiments look for the particles into which neutrons decay.

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

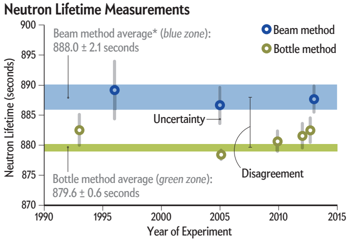
Illustration by Bill Mayer

Two methods to measure the neutron lifetime





Problems to meet ...

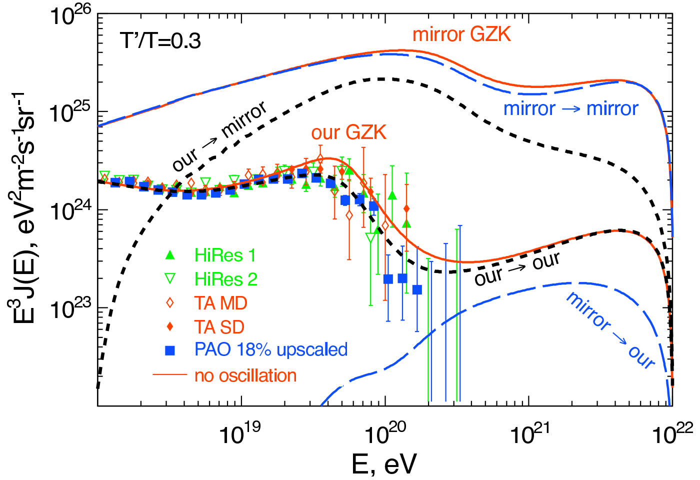


A few theorists have taken this notion seriously. Zurab Berezhiani of the University of L'Aquila in Italy and his colleagues have suggested such a secondary process: a free neutron, they propose, might sometimes transform into a hypothesized "mirror neutron" that no longer interacts with normal matter 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 ? Missing decay channel seems impossible (neutron would be unstable also in nuclei).
But $n \to n'$ conversion can be plausible explanation
$+$ beta-decay of n' in invisible channel

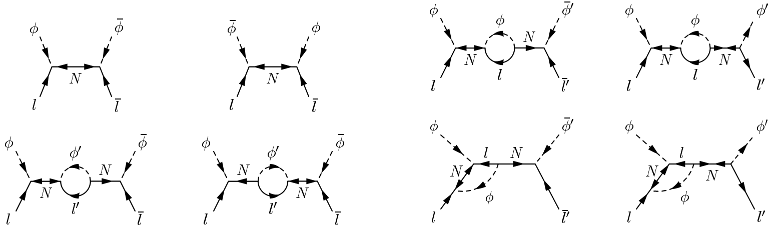
$n - n'$ oscillation in itself cannot destabilise nuclei:
$(A, Z) \to (A-1, Z) + n'(p' e' \bar{\nu}')$ forbidden by energy conservation

Neutron – mirror neutron oscillation in cosmic rays



Theory of cogenesis: 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 $\frac{1}{2}Mg_{jk}N_jN_k + \mathrm{h.c.}$



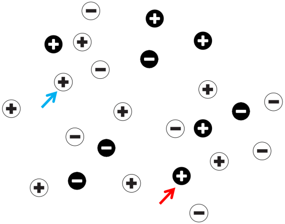
Complex Yukawa couplings $Y_{ij}l_iN_j\bar{\phi} + Y'_{ij}l'_iN_j\bar{\phi}' + \mathrm{h.c.}$

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

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

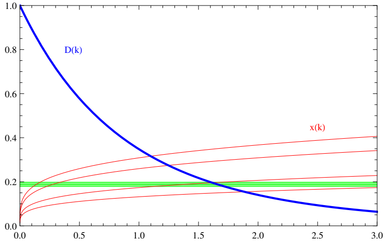
$$\Omega'_B = \Omega_B \simeq 10^3 \frac{J M_{Pl} T_R^3}{M^4} \simeq 10^3 J \left(\frac{T_R}{10^{11}~{\rm GeV}}\right)^3 \left(\frac{10^{13}~{\rm GeV}}{M}\right)^4$$

Cogenesis: $\Omega'_B/\Omega_B \simeq 5$?

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

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

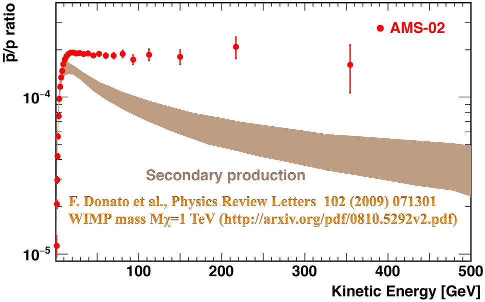
should be solved with Γ:



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

I Mirror matter is a hidden antimatter ... : antimatter in the cosmos?

In mirror cosmic rays, disintegration of mirror nuclei by galactic UV background or in scatterings with mirror gas, frees out mirror neutrons which the oscillate into our antineutron, $n' \to \bar{n}$, which then decays as $\bar{n} \to \bar{p} + \bar{e} + \nu_e$.
so we get antiprotons (positrons), with spectral index similar to that of protons in our cosmic rays ?



Mirror matter can be transformed into our antimatter !!!

Hence, in normal conditions $n' \to n$ oscillation probabilities are tiny, mirror neutrons behave nicely and do not disturb us: everyone stays on his side of the mirror

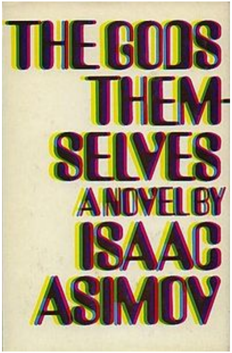
However, under well-controlled vacuum and magnetic conditions, mirror neutrons can be transformed into our antineutrons with reasonable probabilities provided that the oscillation time $n' \to \bar{n}$ is indeed small ... the resulting annihilations give energy, and we can use it

"It does not matter how beautiful your theory is, it does not matter how smart you are ... if it is not confirmed by experiment, it's wrong"

Now it is turn of experimentalists to turn this tale into reality ....
or to exclude it – at least oscillation time $\tau_{nn'} < 10^3$ s

If discovered – impact can be enormous ... One could get plenty of energy out of dark matter !

Appendix



First Part: Against Stupidity ...

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

Third Part: ... Contend in Vain?

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

Summary

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, or dark hydrogen atom into our antihydrogen, etc.

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