Sterile Neutrinos: The Good, The Bad, The Ugly

Zurab Berezhiani

University of L'Aquila and LNGS

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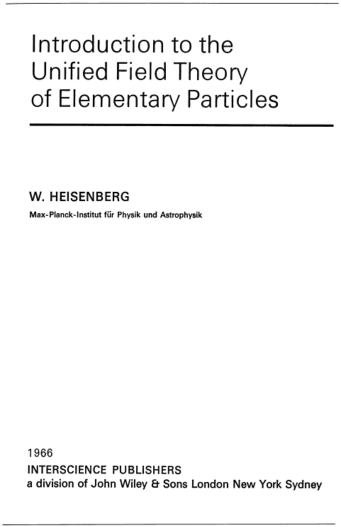
Contents

Neutron $\to$ Neutrino ... 4-fermion β-decay ... Dirac $\to$ Majorana ... neutrino vs antineutrino ...

Why neutrinos are massless?



Introduction to the Unified Field Theory of Elementary Particles

W. HEISENBERG

Max-Planck-Institut für Physik und Astrophysik

1966

INTERSCIENCE PUBLISHERS

a division of John Wiley & Sons London New York Sydney

In a chapter "Weak Interactions" of this book Werner Heisenberg questioned the origin of massless neutrino.

Why neutrino is massless?

... because neutrino is a Goldstone particle

The fact that the neutrino is a neutral particle does not mean that it must be massless. Weyl neutrino can make mass with the antineutrino (Majorana mass). Why then the neutrino is massless ? And then he suggested the following:
" ... this makes to think that the neutrino might play a role of a Goldstone particle emerging due to asymmetry of a ground state ... though here the usual Goldstone argumentation needs to be modified ... and arguments according to which the Goldstone particles must be bosons, probably will be rendered invalid. After all, theory of weak interactions does not exist yet ... In this view, interpretation of neutrino as a Goldstone particle looks very likely."

A crazy idea .... and even wrong !!! But not stupid at all !!!
... we know that neutrinos are not Goldstones ... but it triggered new concept – SUSY and super-Higgs mechanism in SUGRA:
"Is the Neutrino a Goldstone Particle?",
Volkov & Akulov, JETP Lett. 17 (1973) Neutrino = Goldstino

Standard Model of all particles and interactions: $SU(3) \times SU(2) \times U(1)$

But the answer why neutrinos are light lies in Standard Model !



+ quarks and QCD (Gell-Mann et al.)

From Dynamit Prize in 1979
... to the publicity on T-shirts

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

What remains outside the SM ?

Standard Model is theoretically fine, and it perfectly passes all experimental tests. However, it does not capture all phenomena

Among things that remain beyond SM, I mention two main issues:

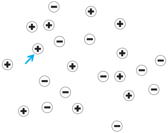
Origin of Matter (matter excess over antimatter in the beginning)

Identitity and origin of dark matter

A great vision ...   1967

Matter (Baryon asymmetry) in the early universe can be originated (from zero) by New Interactions which

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



$\sigma(bb \to \bar{b}\bar{b})/\sigma(\bar{b}\bar{b} \to bb) = 1 - \epsilon$

$\epsilon \sim 10^{-9}$: for every $\sim 10^{9}$ processes *one unit of B* is left in the universe after the process is frozen

Bright & Dark Sides of our Universe

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

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

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

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

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

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

fermions and anti-fermions :

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

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

$\updownarrow$ CP

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

B=–1/3   L=–1   B=–1/3   L=–1

C and P are maximally broken in weak interactions
(not respected by gauge interactions)

but CP: $F_L \to F_R^c \equiv \bar{F}_R = C\overline{F_L}^T = C\gamma_0(F_L)^\dagger$ is a nearly good symmetry
transforming Left-handed matter $\to$ Right-handed antimatter
– broken *only* by complex phases of Yukawa couplings to Higgs doublet ϕ

$$\mathcal{L}_{\rm Yuk} = Y_{ij}\overline{F_{Ri}}F_{Lj}\phi + \text{h.c.} = Y_{ij}\bar{F}_{Li}F_{Lj}\phi + Y_{ij}^* F_{Ri}\bar{F}_{Rj}\phi^\dagger + (M_{ij}\tilde{\nu}_{Li}\tilde{\nu}_{Lj} + \text{h.c.})$$

B and L are automatically conserved in (renormalizable) couplings:
accidental global symmetries $U(1)_B$ and $U(1)_L$

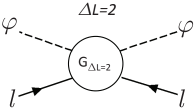
B$-$L is conserved also by non-perturbative effects

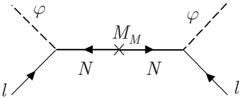
B & L breaking needs New Physics: HO operators $\frac{1}{M}qqq\ell$, $\frac{1}{M}u_R u_R d_R e_R$,

B-L violation: Majorana masses of neutrinos

- $\frac{A}{M}(\ell\phi)(\ell\phi) \quad (\Delta L = 2)$
  induces Majorana masses of neutrinos: $m_\nu \sim v^2/M$
  – seesaw mechanism

$M \simeq 10^{15}$ GeV is the scale of new physics beyond EW scale $\langle\phi\rangle = v$
$\simeq$ Majorana masses of "new" singlet fermions (RH neutrinos)





Back to Sakharov: baryon asymmetry of the Universe can be induced by L and CP-violation in decays: $\Gamma(N \to \ell\phi) \neq \Gamma(N \to \bar{\ell}\bar{\phi})$
"redistributed" to non-zero B via non-perturbative SM effects
– Baryogenesis via Leptogenesis – but the price is rather expensive

Alternative Standard Model $SU(2) \times U(1)$

fermions and anti-fermions :

$$b_L = \begin{pmatrix} p_L \\ n_L \end{pmatrix}, \quad \ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}; \qquad p_R, \; n_R, \qquad e_R, (\nu_R)$$

B=1 L=1 B=1 L=1

$$\tilde{b}_R = \begin{pmatrix} \tilde{p}_R \\ \tilde{n}_R \end{pmatrix}, \quad \bar{\ell}_R = \begin{pmatrix} \bar{\nu}_R \\ \bar{e}_R \end{pmatrix}; \qquad \tilde{p}_L, \; \tilde{n}_L, \qquad \bar{e}_L, (\tilde{\nu}_L)$$

B=–1 L=–1 B=–1 L=–1

$\updownarrow$ CP

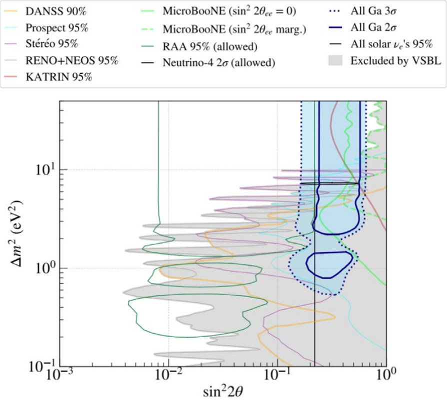
Yukawa couplings to Higgs doublet ϕ

$$\mathcal{L}_{\rm Yuk} = Y_{ij} \bar{F}_{Li} F_{Lj} \phi + \mu_{ij} b_{Li} \ell_{Lj} \tilde{\nu}_{Lj} + M_{ij} \tilde{\nu}_{Li} \tilde{\nu}_{Lj} + M_{ij} n_{Li} n_{Lj} + \text{h.c.}$$

B and L are conservation is no more automatic (in renormalizable couplings):
accidental global symmetries $U(1)_B$ and $U(1)_L$ have gone ....

Sterile neutrinos: Experimental Mess (Ugly)

M. Danilov, Phys. Scr. 97 (2022) 094001



3 + 1 scenario: Athos, Pothos, Aramis ... and ???

Who is this new player in the team ?

Sterile neutrinos: Unknown Identity (Bad)

Definition: Sterile ν is neutral fermion with no weak (SM) interactions (gauge singlet)

Naively extended to assumption that it has no interactions at all... – In other words, sterile ν is taken as really sterile (=not alive)

In SM there are 3 active neutrinos (= LH neutrinos $\nu_L^{e,\mu,\tau}$)

+ 3 sterile neutrinos (= RH neutrinos $\nu_R^{1,2,3} = C\overline{\tilde{\nu}_L^{1,2,3}}$) – mass matrix

$$\left(\begin{array}{c|c} M_{ij} & D_{ij'} \\ \hline D^T_{i'j} & M_{i'j'} \end{array}\right), \qquad D_{ij'} \propto v_{EW}, \quad M_{ij} \propto v^2_{EW}/M, \quad M_{i'j'} \sim M_R$$

In $3+1$ scenario equilibrium is violated:

$$\left(\begin{array}{ccc|c} m_{ee} & m_{e\mu} & m_{e\tau} & m_{es} \\ m_{e\mu} & m_{\mu\mu} & m_{\mu\tau} & m_{\mu s} \\ m_{e\tau} & m_{\mu\tau} & m_{\tau\tau} & m_{\tau s} \\ \hline m_{es} & m_{\mu s} & m_{\tau} & m_{ss} \end{array}\right)$$

Who is ν_s? Why it is (almost) as light as active neutrinos? and how it can have significant (off-diagonal) mixings with actives?

Series of confusionary works with ν_s = modulino, dilatino, axino, etc.

What is then the Good in sterile neutrinos ?

Since we do not know who is it, we can make guess assuming that its existence is necessary for understanding the Universe.

Namely, look for a picture when sterile ν's are light by the same reasons as know active neutrinos, and also can have significant mixings with lights, NATURALLY.

And their existence is useful for understanding the Universe, namely two main issues:

Essential for understanding matter over antimatter asymmetry

It clears the identitity and origin of dark matter

And perhaps relates two issues together, explaining why $\Omega_{DM} \simeq 5\Omega_B$

Light sterile neutrino(s) – analogy to active neutrinos

Active neutrinos are light because because of the SM gauge structure $G = SU(3) \times SU(2) \times U(1)$ and its multiplet content:
their "right-handed" neutrinos (gauge singlets) are heavy Majorana.
See-saw mechanism induces D=5 Weinberg operator $\frac{1}{M}\ell\ell\phi\phi$

So, neutrinos get small Majorana masses $m_\nu \sim v^2/M$,
quadratic in EW scale $\langle\phi\rangle = v$.

This makes to think that sterile neutrino(s) are light because in fact they are not really sterile (= gauge singlets). Instead, they have interactions with some hidden/dark gauge sector (i.e. are not singlets with respect a dark gauge group G' perhaps like SM) and their masses cannot be induced without breaking of some gauge symmetry at some lower scale $v' \sim v$.
In fact, we want to have $m_s \sim v'^2/M$

The natural possibility is to consider Mirror sector
with $G' = SU(3)' \times SU(2)/ \times U(1)'$

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 .... (Candid, Frank and Uncontrived)

Dark matter from parallel gauge sector ?
$G' = SU(3)' \times SU(2)' \times U(1)'$? (+ 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 ?
Another Best of the possible Worlds? (Maybe Candide had a twin?)

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

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

$E_8 \times E'_8$

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

Two parities

Fermions and anti-fermions :

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

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

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

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

Twin Fermions and anti-fermions :

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

B′=1/3 L′=1 B′=1/3 L′=1

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

B′=-1/3 L′=-1 B′=-1/3 L′=-1

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

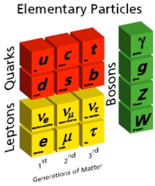
Z_2 symmetry $(L, R \to L, R)$: $Y' = Y$ $\quad B - B' \to -(B - B')$

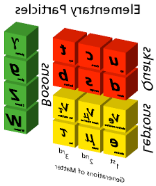
PZ_2 symmetry $(L, R \to R, L)$: $Y' = Y^*$ $\quad B - B' \to B - B'$

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

$$G \times G'$$

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 :

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

But all is OK if : Z.B., Dolgov, Mohapatra, 1995 *(broken Z_2)*
Z.B., Comelli, Villante, 2000 *(exact Z_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

$T'/T < 0.5$ from BBN, but cosmological limits $T'/T < 0.2$ or so.

$x = T'/T \ll 1 \quad \Longrightarrow$ 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

Brief Cosmology of Mirror World

• CMB & (linear) structure formation epoch
Since $x = T'/T \ll 1$, mirror photons decouple before M-R equality:
$z'_{\rm dec} \simeq x^{-1} z_{\rm dec} \simeq 1100\,(T/T')$
After that (and before M–reionization) M matter behaves as collisionless CDM and $T'/T < 0.2$ is consistent with Planck, BAO, Ly-α etc.

• Cosmic dawn: M world is colder (and helium dominated), the first M star can be formed earlier and reionize M sector ($z'_{\rm r} \simeq 20$ or so vs $z_{\rm r} = 10 \div 6$). – EDGES 21 cm at $z \simeq 17$?
Heavy first M stars ($M \sim 10^3 M_\odot$) and formation of central BH – Quasars?

• Galaxy halos? 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 dominated by BH and M stars, with our matter forming disks inside.
Maybe not always: Galaxies with missing DM, or too many DM, etc. ?

Because of $T' < T$, the situation $\Omega'_B \simeq 5\Omega_B$ becomes plausible in baryogenesis. So, M matter can be dark matter (as we show below)

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?

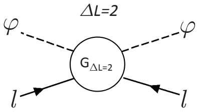
B. *Direct detection.* M matter can interact with ordinary matter e.g. via kinetic mixing $\epsilon F^{\mu\nu} F'_{\mu\nu}$, etc. Mirror helium as most abundant mirror matter particles (the region of DM masses below 5 GeV is practically unexplored). Possible signals from heavier nuclei C,N,O etc.

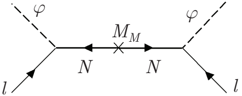
C. *Oscillation phenomena between ordinary and mirror particles.*
The most interesting interaction terms in $\mathcal{L}_{\rm mix}$ are the ones which violate B and L of both sectors. Neutral particles, elementary (as e.g. neutrino) or composite (as the neutron or hydrogen atom) can mix with their mass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

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

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

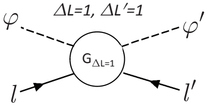
M is the (seesaw) scale of new physics beyond EW scale.





- 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

Mixing pattern

Nowe we have 3 active neutrinos ($\nu_{e,\mu,\tau}$)
+ 3 sterile neutrinos (= mirror neutrinos $\nu'_{e,\mu,\tau}$)
Gauge singlet (heavy) neutrinos are integrated out as in seesaw.

$\frac{A}{M}(l\bar{\phi})(l\bar{\phi})$, $\frac{D}{M}(l'\bar{\phi}')(l'\bar{\phi}')$ and $\frac{A'}{M}(l\bar{\phi})(l'\bar{\phi}')$

Total mass matrix

$$\left(\begin{array}{c|c} M_{ij} & D_{ij'} \\ \hline D^T_{i'j} & M'_{i'j'} \end{array}\right) = \frac{1}{M}\left(\begin{array}{c|c} Av^2 & Dvv' \\ \hline D^T vv' & A'v'^2 \end{array}\right) \sim \left(\begin{array}{c|c} m_\nu & \xi m_\nu \\ \hline \xi m_\nu & \xi^2 m_\nu \end{array}\right), \quad \xi =$$

Akhmedov, ZB, Senjanovic. 1992
ZB, Mohapatra, 1995

$\xi = v'/v \gg 1$: $\quad m'_\nu \sim \xi^2 m_\nu$, $\quad \sin\theta_{\nu\nu'} \sim v/v' = 1/\xi$

$\xi = 1$: $m'_\nu = m_\nu$, and active-sterile mixing is nearly maximal

Mirror supernove: Antineutrino (neutronization) bursts ?
depends on the sign of BA in mirror sector ZB, Pagliaroli, in progress

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

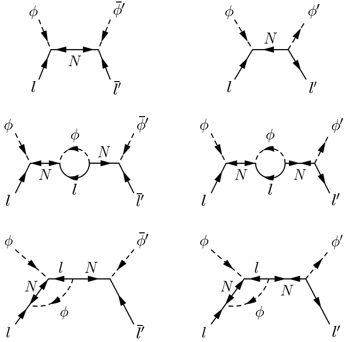
Green light to celebrated conditions of Sakharov

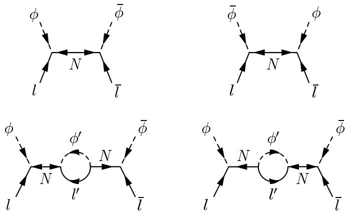
Z.B. and Bento, PRL 87, 231304 (2001)

Co-leptogenesis:

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

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





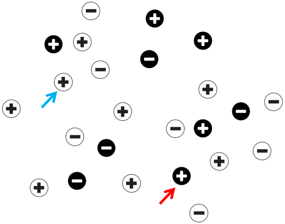
Complex Yukawa couplings $Y_{ij}l_iN_j\bar{\phi} + Y'_{ij}l'_iN_j\bar{\phi}' + \mathrm{h.c.}$

Z_2 (Xerox) symmetry $\rightarrow Y' = Y$,
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*



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

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

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

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

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

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

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

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

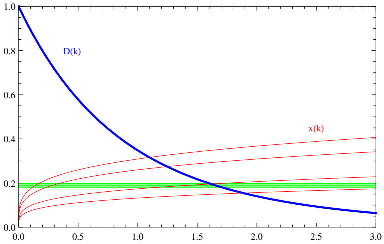
$$\Omega'_B = \Omega_B \simeq 10^3 \frac{J M_{Pl} T_R^3}{M^4} \simeq 10^3 J \left(\frac{T_R}{10^{11}\ \mathrm{GeV}}\right)^3 \left(\frac{10^{13}\ \mathrm{GeV}}{M}\right)^4$$

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

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

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

should be solved with Γ:



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

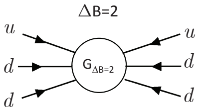
Neutron – mirror neutron mixing

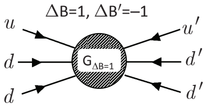
B violating operators between O and M particles in $\mathcal{L}_{\rm mix}$

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

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

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

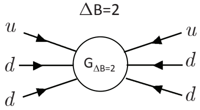




Oscillations $n \to \bar{n}$ $(\Delta B = 2)$
Oscillations $n \to \bar{n}'$ $(\Delta B = 1,\ \Delta B' = -1)$ $B + B'$ is conserved

Neutron– antineutron mixing

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



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

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

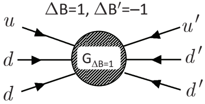
Key moment: *$n - \bar{n}$ oscillation destabilizes nuclei:*
$(A, Z) \to (A-1, \bar{n}, Z) \to (A-2, Z/Z-1) + \pi$'s

Present bounds on ϵ from nuclear stability

$\varepsilon < 1.2 \times 10^{-24}$ eV	$\to$	$\tau > 1.3 \times 10^8$ s	Fe, Soudan 2002
$\varepsilon < 2.5 \times 10^{-24}$ eV	$\to$	$\tau > 2.7 \times 10^8$ s	O, SK 2015
$\varepsilon < 7.5 \times 10^{-24}$ eV	$\to$	$\tau > 0.9 \times 10^8$ s	direct limit free n

Neutron – mirror neutron mixing

Effective operator $\frac{1}{M^5}(udd)(u'd'd')$ $\rightarrow$ 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)

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

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

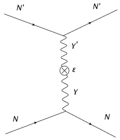
these terms can be limited (only) by experiment/cosmology !

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

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

$\epsilon < 3 \times 10^{-7}$ (EXP) $\qquad \epsilon < 5 \times 10^{-9}$ (COSM)

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



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)

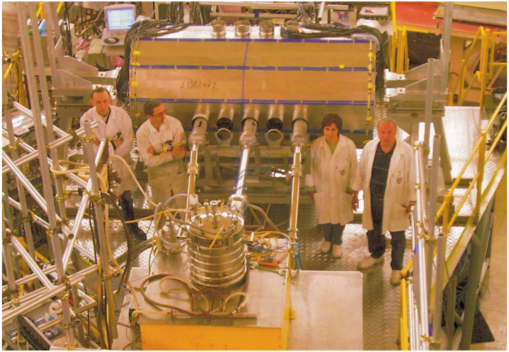
$\lambda S(\phi_1\phi_2 + \phi'_1\phi'_2) + \Lambda S + \ldots$

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

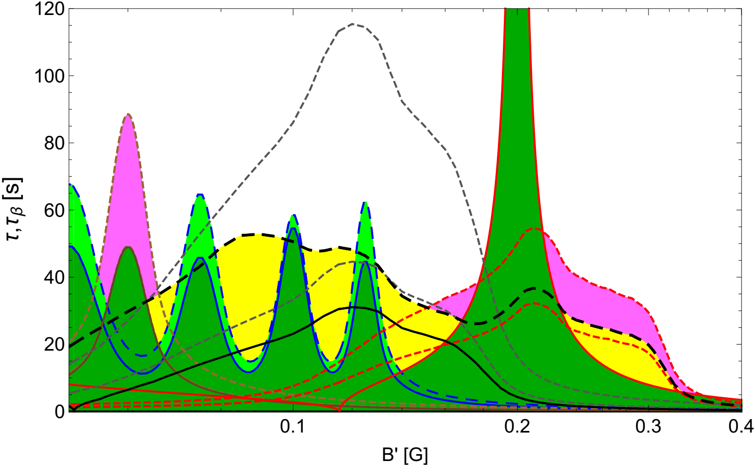
- Neutron-neutron′ mixing – discussed later

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



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



Free Neutrons: Where to find Them ?

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

But most of neutrons bound in nuclei ....

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

Free neutrons are present only in

- Reactors and Spallation Facilities
- In Cosmic Rays
- During BBN epoch (fast $n' \to \bar{n}$ can solve Lithium problem)

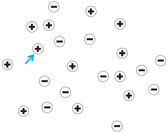
– Transition $n \to \bar{n}'$ can take place for (gravitationally) Neutron Stars – conversion of NS into mixed ordinary/mirror NS

Matter and antimatter in the Universe

Matter – Antimatter Asymmetry in the Universe

Matter (Baryon asymmetry) in the early universe can be originated (from zero) by New Interactions which

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



$\sigma(bb \to \bar{b}\bar{b})/\sigma(\bar{b}\bar{b} \to bb) = 1 - \epsilon$

$\epsilon \sim 10^{-9}$: for every $\sim 10^{9}$ processes *one unit of B* is left in the universe after the process is frozen

There should be no antimatter in the Universe!

In any case, matter should dominate the entire visible Universe

No antimatter domain can exist within the horizon!

– Cohen, De Rujula, Glashow 1997

Antinuclei in Cosmic Rays ... AMS-02

Eight anti-helium candidates were observed by AMS-02:

6 helium-3 and 2 helium-4 with energies $\sim$ GeV

$\Phi(\overline{\rm He})/\Phi({\rm He}) \sim 10^{-8}$ – no anti deuteron candidate

$\Phi({\rm He}) \sim 10^3~{\rm cm^{-2}s^{-1}sr^{-1}}$

Discovery of a single anti-He-4 nucleus challenges all known physics.

AMS-02 signal (once published) should point to highly non-trivial New Physics

LHC: Deuteron and triton-He3 are produced in *pp* collisions (in minuscule fractions) – but no He4 was ever seen ...

My hypothesis ...

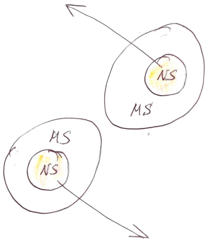
- DM from a hidden gauge sector having physics $\sim$ to ordinary matter:

SM $\times$ SM$'$ $\quad e, p, n, \nu .. \leftrightarrow e', p', n', \nu'$ $\quad SU(5) \times SU(5)', \dots\ E_8 \times E_8'$

- Neutron stars (NS) exist and NS-NS gravitational mergers are observed
- There exist dark neutron stars (NS$'$) built of mirror neutrons n'
- Neutron–mirror neutron mixing induces $n' \to \bar{n}$ transition

– antimatter "eggs" grow inside NS$'$ – a small antistar inside NS$'$

- NS$'$-NS$'$ mergers "liberate" the anti-nuclei with $v \sim c$
- $\Phi_{\bar{b}} \sim R(\mathrm{NS}' - \mathrm{NS}') \times N_{\bar{b}}^{\mathrm{NS}} \times \tau_{\mathrm{surv}} \times c \sim ??$ $\qquad \tau_{\mathrm{surv}} < 14$ Gyr



How large the antinuclear flux can be ?

- $\Phi_{\bar{b}} \sim R(\mathrm{NS}'-\mathrm{NS}') \times N_{\bar{b}}^{\mathrm{NS}} \times \tau_{\mathrm{surv}} \times c$

Merger rate:
$R(\mathrm{NS}'-\mathrm{NS}') \sim R(\mathrm{NS}-\mathrm{NS}) \sim 10^3 \ \mathrm{Gpc}^{-3} \ \mathrm{yr}^{-1}$

Amount of antibarions produced in NS′
$N_{\bar{b}} \sim N_0 \times (t_{\mathrm{NS}}/\tau_\varepsilon) \sim 3 \cdot 10^{52} \times (t_{\mathrm{NS}}/10^{10}\,\mathrm{yr})\,(10^{15}\,\mathrm{yr}/\tau_\varepsilon)$

Survival time:
$\tau_{\mathrm{surv}} = (n_p \langle \sigma_{\mathrm{ann}} v \rangle)^{-1} \simeq 3 \cdot 10^{14} \times (1\ \mathrm{cm}^{-3}/n_p)$ $\quad t_{\mathrm{NS}}, \tau_{\mathrm{surv}} < 14$ Gyr

- $\Phi_{\bar{b}} \sim \left(\frac{R}{10^3\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}}\right) \left(\frac{N_{\bar{b}}}{10^{53}}\right) \left(\frac{\tau_{\mathrm{surv}}}{10^{17}\,\mathrm{s}}\right) \times 10^{-6}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Transforming Dark Matter into Antimatter: n or $\bar{n}$?

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

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

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

Such transitions in mirror NS create O matter cores. If baryon asymmetry in M sector has opposite sign, transitions $\bar{n}' \to \bar{n}$ create antimatter cores which can be seen by LAT by accreting ordinary gas and explain the origin of anti-helium nuclei in cosmic rays supposedly seen by AMS2

Summary

$n - n'$ conversion also has interesting implications for the neutron stars (gradual conversion of the neutron stars into mixed ordinary-mirror stars till achieving "fifty-fifty" mixed twin star configuration with $\sqrt{2}$ times smaller radius and $\sqrt{2}$ smaller maximal mass

Remarkably, it can be tested in laboratories via looking for anomalous (magnetic field dependent) disappearance of the neutrons (for which there already exist some experimental indications, most remarkable at the 5.2σ level) due to $n \to n'$ conversion and and "walking through the wall" experiments ($n \to n' \to n$ regeneration). $n - n'$ oscillation can be also related to the neutron lifetime puzzle.

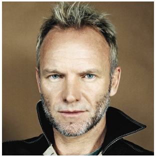
6 helium-3 and 2 helium-4 with energies $\sim$ GeV

$\Phi(\overline{\mathrm{He}})/\Phi(\mathrm{He}) \sim 10^{-8}$ – no anti deuteron candidate

Discovery of a single anti-He-4 nucleus challenges all known physics.

AMS-02 signal (once published) will bring to a revolution in Physics

S Ting promised that AMS-02 will publish the anti-nuclei data as soon as they see first anti-carbon



My scenario is optimistic – this depends in burning conditions in antimatter core for nuclear reactions – depends on age, central density etc. – First it should start to produce helium as in the Sun (without initial Helium) – but then it can go to produce C-N-O and perhaps further ...

Everything is very simple as possible – but not simpler

Getting Energy from Dark Parallel World

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

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

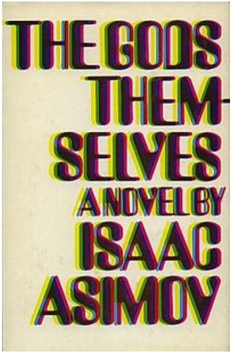
dark neutrons, before they decay, can be effectively transformed into our antineutrons in controllable way, by tuning vacuum and magnetic fields, if $\tau_{n\bar{n}'} < 10^3$ s

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

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

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

Asimov Machine: the "Pump"



First Part: Against Stupidity ...

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

Third Part: ... Contend in Vain?

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

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

Thanks

Many Thanks for Listening

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