



On the origin of
cosmic
antimatter

Zurab Berezhiani

Summary

On the origin of cosmic antimatter

Zurab Berezhiani

University of L'Aquila and LNGS

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Anti-particles and anti-matter (antinulei)

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From discovery of positron, 1930-32

*and all other antiparticles
(antiproton, antineutron etc.)*



$$\left(i\hbar \frac{\partial}{\partial t} + \sum_{\alpha} \alpha_{\alpha} p_{\alpha} \right) \psi(\mathbf{x}, t) = i\hbar \frac{\partial \psi(\mathbf{x}, t)}{\partial t}$$



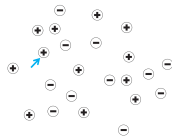
... to a great vision 1967

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

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

$\epsilon \sim 10^{-9}$: 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

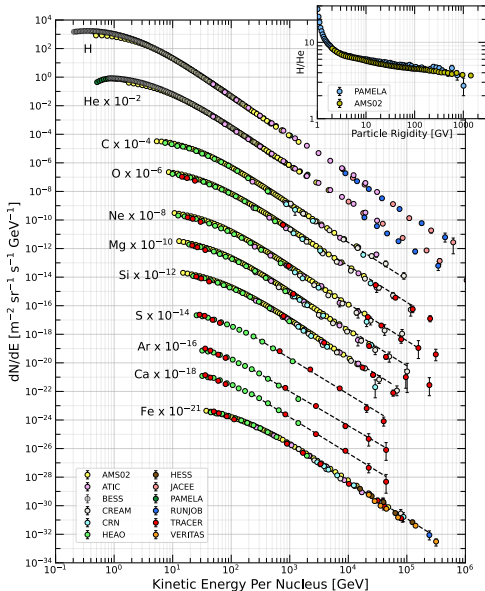


Protons and Nuclei in cosmic rays

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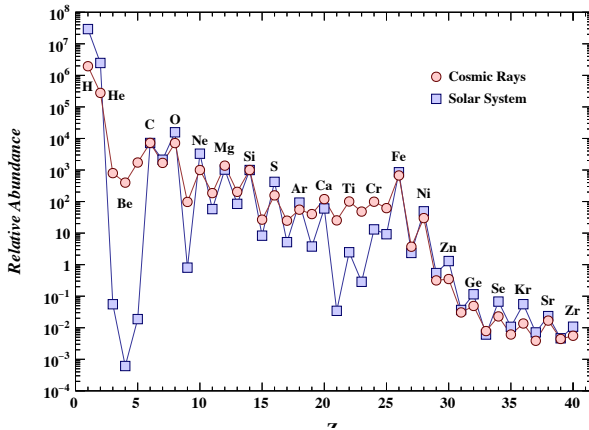


Abundances: in cosmic rays vs. cosmological

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Antiprotons in Cosmic Rays

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$$\Phi_{\bar{p}}/\Phi_p \sim 10^{-4}$$

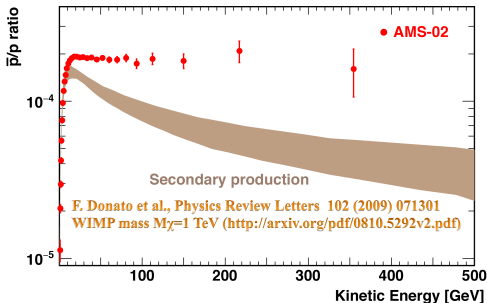
AMS-02

can be produced as secondaries in collisions of cosmic rays with interstellar gas, or can be signature of Dark Matter annihilation?

WIMP + WIMP to proton + antiproton? (electron + positron?)

$M_\chi \sim \text{few hundred GeV}$

Anti-deuteron test?





Antinuclei in Cosmic Rays ... AMS-02

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

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

$\Phi(\overline{\text{He}})/\Phi(\text{He}) \sim 10^{-8}$ – no anti deuteron candidate
 $\Phi(\text{He}) \sim 10^3 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$

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 ...

Some *specifically tuned* DM models could explain the flux of
antihelium-3 – but hard for antihelium-4 !



My hypothesis ...

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- There are dark stars (composed of DM) in the Universe
- They contain small antimatter eggs in their interiors (compressed by dark star gravity) – observable as a small antistar inside (invisible) dark star
- Gravitational mergers of dark stars "liberate" antimatter from their cores so producing anti-nuclei in cosmic rays



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

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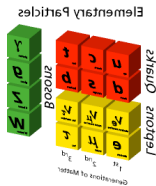
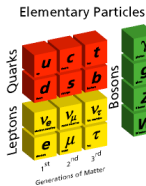
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Summary

$$G \times G'$$

Regular world

Mirror world



- Two identical gauge factors, e.g. $SU(5) \times SU(5)'$, with identical field contents and Lagrangians: $\mathcal{L}_{\text{tot}} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\text{mix}}$
- Mirror sector (\mathcal{L}') is dark – or perhaps grey? ($\mathcal{L}_{\text{mix}} \rightarrow$ portals)
- MM is similar to standard matter (asymmetric/dissipative/atomic) but realized in somewhat different cosmological conditions ($T'/T \ll 1$)
- $G \leftrightarrow G'$ symmetry no new parameters in \mathcal{L}'
- Cross-interactions between O & M particles
 \mathcal{L}_{mix} : new operators – new parameters! limited only by experiment!



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

Matter and Antimatter

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fermions and anti-fermions :

$$\begin{array}{llll}
 q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, & \ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}; & u_R, & d_R, & e_R \\
 \text{B}=1/3 & \text{L}=1 & \text{B}=1/3 & & \text{L}=1 \\
 \bar{q}_R = \begin{pmatrix} \bar{u}_R \\ \bar{d}_R \end{pmatrix}, & \bar{\ell}_R = \begin{pmatrix} \bar{\nu}_R \\ \bar{e}_R \end{pmatrix}; & \bar{u}_L, & \bar{d}_L, & \bar{e}_L \\
 \text{B}=-1/3 & \text{L}=-1 & \text{B}=-1/3 & & \text{L}=-1
 \end{array}$$



\updownarrow CP



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

but CP: $F_L \rightarrow F_L^c \equiv \bar{F}_R = C \bar{F}_L^T = C \gamma_0 (F_L)^*$ is a nearly good symmetry
transforming Left-handed matter \rightarrow Right-handed antimatter

– broken *only* by complex phases of Yukawa couplings to Higgs doublet ϕ

$$\mathcal{L}_{\text{Yuk}} = Y_{ij} \bar{F}_{Ri} F_{Lj} \phi = Y_{ij} \bar{F}_{Li} F_{Lj} \phi + \text{h.c.} \quad + \theta\text{-term in QCD}$$

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



B-L violation: Majorana masses of neutrinos

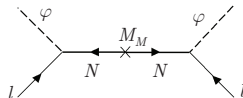
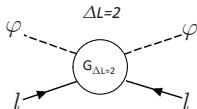
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- $\frac{A}{M}(\ell\phi)(\ell\phi) \quad (\Delta L = 2)$
induces Majorana masses of
neutrinos: $m_\nu \sim v^2/M$
– seesaw mechanism

$M \simeq 10^{15}$ 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:** $\Gamma(N \rightarrow \ell\phi) \neq \Gamma(N \rightarrow \bar{\ell}\bar{\phi})$
"redistributed" to non-zero B via non-perturbative SM effects
– **Baryogenesis via Leptogenesis** – but the price is rather expensive



$$SU(3) \times SU(2) \times U(1) \quad \text{vs.} \quad SU(3)' \times SU(2)' \times U(1)'$$

Two possible parities: with and without chirality change

fermions and anti-fermions :

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

$B=1/3 \qquad L=1 \qquad B=1/3 \qquad L=1$



\updownarrow CP

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

$B=-1/3 \qquad L=-1 \qquad B=-1/3 \qquad L=-1$



Mirror fermions and antifermions :

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

$B'=1/3 \qquad L'=1 \qquad B'=1/3 \qquad L'=1$



\updownarrow CP

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

$B'=-1/3 \qquad L'=-1 \qquad B'=-1/3 \qquad L'=-1$



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

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

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



– Sign of mirror baryon asymmetry ?

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Ordinary BA is positive: $\mathcal{B} = \text{sign}(n_b - n_{\bar{b}}) = 1$
– as produced by (unknown) baryogenesis a la Sakharov!

Sign of mirror BA, $\mathcal{B}' = \text{sign}(n_{b'} - n_{\bar{b}'}),$ is a priori unknown!

Imagine a baryogenesis mechanism *separately* acting in O and M sectors!
– without involving cross-interactions in \mathcal{L}_{mix}

E.g. leptogenesis $N \rightarrow \ell \phi$ and $N' \rightarrow \ell' \phi'$

$Z_2: \rightarrow Y'_{u,d,e} = Y_{u,d,e}$ i.e. $\mathcal{B}' = 1$

– O and M sectors are CP-identical in same chiral basis O=left, M=left

$Z_2^{LR}: \rightarrow Y'_{u,d,e} = Y_{u,d,e}^*$ i.e. $\mathcal{B}' = -1$

– O sector in L-basis is identical to M sector in R-basis O=left, M=right

In the absence of cross-interactions in \mathcal{L}_{mix} we cannot measure sign of BA
(or chirality in weak interactions) in M sector – so all remains academic ...

But switching on cross-interactions, violating B/L & $\mathcal{B}'/-L'$ – as mixings
neutron–neutron' $\in nn' + \text{h.c.}$ $\Delta(\mathcal{B}-\mathcal{B}') = 0$ or $\nu\nu' + \text{h.c.}$ $\Delta(\mathcal{L}-\mathcal{L}') = 0$

$\mathcal{B}' = -1 \rightarrow \bar{n}' \rightarrow n$ M (anti)matter \rightarrow O matter but $\bar{\nu}' \rightarrow \bar{\nu}$

$\mathcal{B}' = 1 \rightarrow n' \rightarrow \bar{n}$ M matter \rightarrow O antimatter but $\nu' \rightarrow \nu$



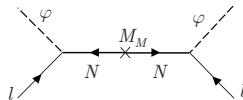
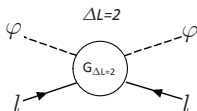
B-L violation in O and M sectors: Active-sterile mixing

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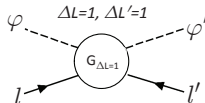
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Summary

- $\frac{A}{M}(\ell\phi)(\ell\phi)$ ($\Delta L = 2$) – neutrino (seesaw) masses $m_\nu \sim v^2/M$
M is the (seesaw) scale of new physics beyond EW scale.



- Neutrino -mirror neutrino mixing – (active - sterile mixing)
L and L' violation: $\frac{A}{M}(\ell\phi)(\ell\phi)$, $\frac{A}{M}(\ell'\phi')(\ell'\phi')$ and $\frac{B}{M}(\ell\phi)(\ell'\phi')$



Mirror neutrinos as natural candidates for sterile neutrinos



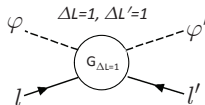
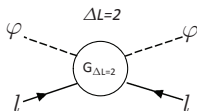
Co-leptogenesis: B-L violating interactions between O and M worlds

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Summary

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



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

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

Green light to celebrated conditions of Sakharov



Co-leptogenesis:

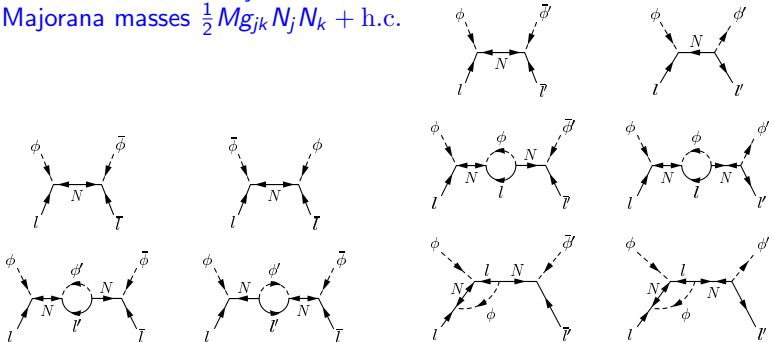
Z.B. and Bento, PRL 87, 231304 (2001)

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Summary

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



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

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

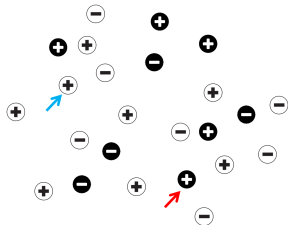
Z_2^{LR} (Mirror) symmetry $\rightarrow Y' = Y^*$



Co-leptogenesis: Sign of Mirror BA

Z.B., arXiv:1602.08599

Hot O World \rightarrow *Cold M World*



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

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

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

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

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

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

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

Mirror (Z_2^{LR}): $Y' = Y^* \rightarrow \Delta\sigma' = -\Delta\sigma \rightarrow B > 0, B' > 0$

Xerox (Z_2): $Y' = Y \rightarrow \Delta\sigma' = \Delta\sigma = 0 \rightarrow B, B' = 0$

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

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

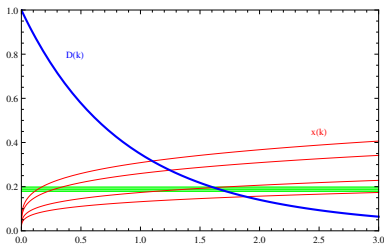


If $k = \left(\frac{\Gamma_2}{H}\right)_{T=T_R} \sim 1$, Boltzmann Eqs.

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

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

should be solved with Γ :



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

So we obtain $\Omega'_B = 5\Omega_B$ when $m'_B = m_B$ but $n'_B \simeq 5n_B$

– the reason: mirror world is colder

Alternative: $n'_B \simeq n_B$ but $m'_B \simeq 5m_B$ – if mirror parity is broken
and $v'/v \sim 10^2$ (case of Little Higgs)



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

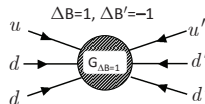
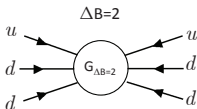
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- Neutron-mirror neutron mixing – (active - sterile neutrons)

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



Oscillations $n \rightarrow \bar{n}$ ($\Delta B = 2$)

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

Exp. bounds on $n - \bar{n}$ oscillation $\tau = \varepsilon^{-1}$ –oscillation time

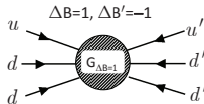
$\varepsilon < 7.5 \times 10^{-24} \text{ eV}$ \rightarrow $\tau > 0.86 \times 10^8 \text{ s}$ direct limit free n

$\varepsilon < 2.5 \times 10^{-24} \text{ eV}$ \rightarrow $\tau > 2.7 \times 10^8 \text{ s}$ nuclear stability



Neutron – mirror neutron mixing

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



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

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 $\epsilon^{-1} = \tau_{nn'} \sim 1 \text{ s}$
 without contradicting experimental and astrophysical limits.
 (c.f. $\tau > 10 \text{ yr}$ 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

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Free Neutrons: Where to find Them ?

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

But most of neutrons bound in nuclei

$n \rightarrow \bar{n}'$ conversions can be seen only with free neutrons ... and, under some parameters, it can explain the neutron lifetime puzzle !

Free neutrons are present only in

- Reactors and Spallation Facilities (experiments are looking for)
- In Cosmic Rays ($n - n'$ in TA and Auger experiments)
- During BBN epoch (fast $n' \rightarrow \bar{n}$ can solve Lithium problem)

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

We do not observe the strong effects since $n \rightarrow \bar{n}'$ is suppressed by some environmental factors (matter, magnetic field) or simply by some mass splitting between $n - n'$



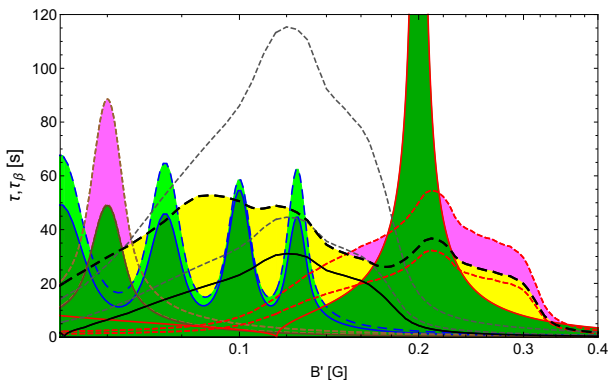
Experiments

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By now ~ 15 different experiments were done at ILL/PSI/ORNL



Several new experiments are underway at PSI, ILL and ORNL
and are planned at ESS



Neutron Stars: $n - n'$ conversion

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Two states, n and n'

$$H = \begin{pmatrix} E(n_b) + \mu_n \vec{B} \vec{\sigma} & \varepsilon \\ \varepsilon & E'(n_{b'}) + \mu_n \vec{B}' \vec{\sigma} \end{pmatrix}$$

$$n_1 = \cos \theta n + \sin \theta n', \quad n_2 = \sin \theta n - \cos \theta n', \quad \theta \simeq \frac{\varepsilon}{E - E'}$$

Fermi degenerate neutron liquid $p_F \simeq (n_b/0.3 \text{ fm}^{-3})^{2/3} \times 400 \text{ MeV}$

$nn \rightarrow nn'$ with rate $\Gamma = 2\theta^2 \eta \langle \sigma v \rangle n_b$

$$\frac{dN}{dt} = -\Gamma N \quad \frac{dN'}{dt} = \Gamma N \quad N + N' = N_0 \text{ remains Const.}$$

$$\tau_\epsilon = \Gamma^{-1} \sim \epsilon_{15}^{-2} \times 10^{15} \text{ yr} \quad N'/N_0 = t/\tau_\epsilon$$

for $t = 10 \text{ Gyr}$, $\tau_\epsilon = 10^{15} \text{ yr}$ gives M fraction 10^{-5} – few Earth mass

$$\dot{\mathcal{E}} = \frac{E_F N}{\tau_\epsilon} = \left(\frac{10^{15} \text{ yr}}{\tau_\epsilon} \right) \times 10^{31} \text{ erg/s} \quad \text{NS heating – surface T}$$



Neutron Star transformation

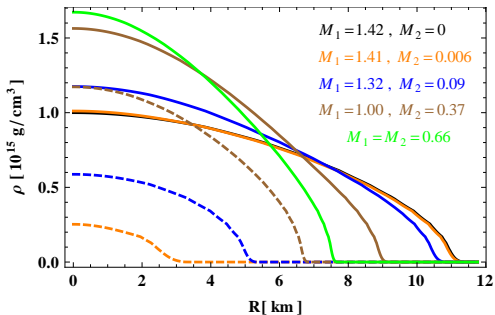
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$$\frac{dN}{dt} = -\Gamma N \quad \frac{dN'}{dt} = \Gamma \quad N + N' = N_0 \quad \text{remains Const.}$$

Initial state $N = N_0, N' = 0$ final state $N = N' = \frac{1}{2}N_0$





Mixed Neutron Stars: TOV and $M - R$ relations

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Summary

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

$$T_{\mu\nu} = T_{\mu\nu}^1 + T_{\mu\nu}^2 = \text{diag}(\rho g_{tt}, p g_{rr}, p r^2, p r^2 \sin^2 \theta)$$

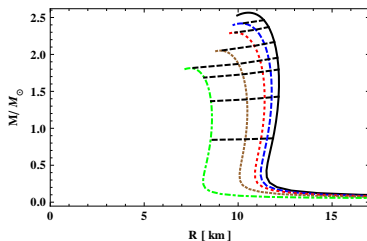
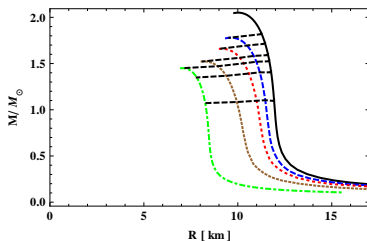
$$\rho = \rho_1 + \rho_2 \quad \& \quad p = p_1 + p_2, \quad p_\alpha = F(\rho_\alpha)$$

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

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

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

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



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



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

On the origin of
cosmic
antimatter

Zurab Berezhiani

Summary

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

Oscillation $n \rightarrow n'$ 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 losses observed in some experiments and paradoxes in the UHECR detections

$n \rightarrow n'$ 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 $\bar{n}' \rightarrow \bar{n}$ 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**



Looking for antimatter stars/planets

On the origin of
cosmic
antimatter

Zurab Berezhiani

Summary

DUPOURQUÉ, TIBALDO, and VON BALLMOOS

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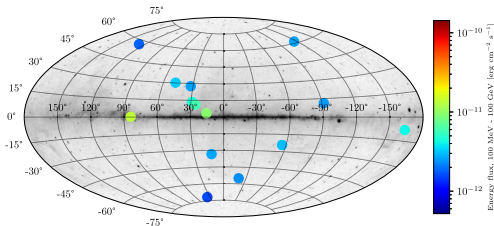


FIG. 1. Positions and energy flux in the 100 MeV–100 GeV range of antistar candidates selected in 4FGL-DR2. Galactic coordinates. The background image shows the *Fermi* 5-year all-sky photon counts above 1 GeV (image credit: NASA/DOE/Fermi LAT Collaboration).

$$\text{Antimatter production rate: } \dot{N}_{\bar{b}} = \frac{N_0}{\tau_{\epsilon}} \simeq \epsilon_{15}^2 \left(\frac{M}{M_{\odot}} \right)^{2/3} \times 3 \cdot 10^{34} \text{ s}^{-1}$$

$$\text{ISM accretion rate: } \dot{N}_b \simeq \frac{(2GM)^2 n_{\text{is}}}{v^3} \simeq \frac{10^{32}}{v_{100}^3} \times \left(\frac{n_{\text{is}}}{1/\text{cm}^3} \right) \left(\frac{M}{M_{\odot}} \right)^2 \text{ s}^{-1}$$

Annihilation γ -flux from the mirror NS as seen at the Earth:

$$J \simeq \frac{10^{-12}}{v_{100}^3} \left(\frac{n_{\text{is}}}{1/\text{cm}^3} \right) \left(\frac{M}{1.5 M_{\odot}} \right)^2 \left(\frac{50 \text{ pc}}{d} \right)^2 \frac{\text{erg}}{\text{cm}^2 \text{ s}} \quad d - \text{distance to source}$$



Mergers of NS .. and mirror NS

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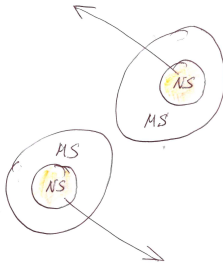
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Summary

NS-NS merger and kilonova (GW170817 ?)
r-processes can give heavy *trans-Iron* elements

Mirror NS-NS merger is invisible (GW190425 ? $M_{\text{tot}} = 3.4M_{\odot}$)

But not completely ... if during the evolution they developed small
core of our **antimatter** (depends on the mirror BA sign)
– their mergers can be origin of antinuclei for AMS-2





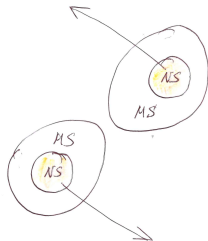
My hypothesis ...

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Summary

- 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 $n' \rightarrow \bar{n}$ transition
– antimatter "eggs" grow inside NS' – a small antistar inside NS'
- NS'-NS' mergers "liberate" the anti-nuclei with $v \sim c$
- $\Phi_{\bar{b}} \sim R(NS' - NS') \times N_b^{NS} \times \tau_{\text{surv}} \times c \sim ?? \quad \tau_{\text{surv}} < 14 \text{ Gyr}$





How large the antinuclear flux can be ?

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Zurab Berezhiani

Summary

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

Merger rate:

$$R(NS' - NS') \sim R(NS - NS) \sim 10^3 \text{ Gpc}^{-3} \text{ yr}^{-1}$$

Amount of antibarions produced in NS'

$$N_{\bar{b}} \sim N_0 \times (t_{NS}/\tau_{\varepsilon}) \sim 3 \cdot 10^{52} \times (t_{NS}/10^{10} \text{ yr}) (10^{15} \text{ yr}/\tau_{\varepsilon})$$

Survival time:

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

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



Antinuclei in Cosmic Rays ... AMS-02

On the origin of
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Summary

6 helium-3 and 2 helium-4 with energies \sim GeV
 $\Phi(\overline{\text{He}})/\Phi(\text{He}) \sim 10^{-8}$ – 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

STing 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

On the origin of
cosmic
antimatter

Zurab Berezhiani

Summary

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 $n \rightarrow \bar{n}'$ (which is the antiparticle for M observer)

while n' (of M matter) oscillates $n' \rightarrow \bar{n}$ 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

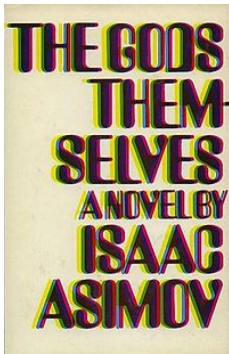


Asimov Machine: the "Pump"

On the origin of
cosmic
antimatter

Zurab Berezhiani

Summary



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 ...