Matter, dark matter and antimatter in the Universe and the origin of antinuclei in cosmic rays

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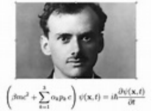
Contents

Anti-particles and anti-matter (antinulei)

From discovery of positron, 1930-32

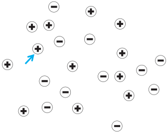


and all other antiparticles (antiproton, antineutron etc.)

... 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



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

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

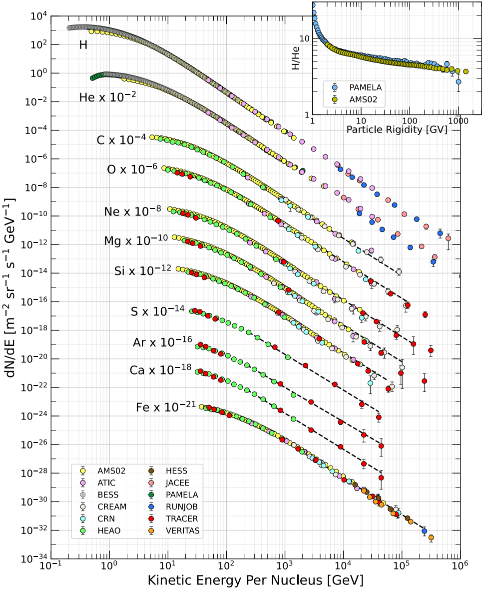
There should be no antimatter in the Universe!

In any case, matter should dominate the entire visible Universe

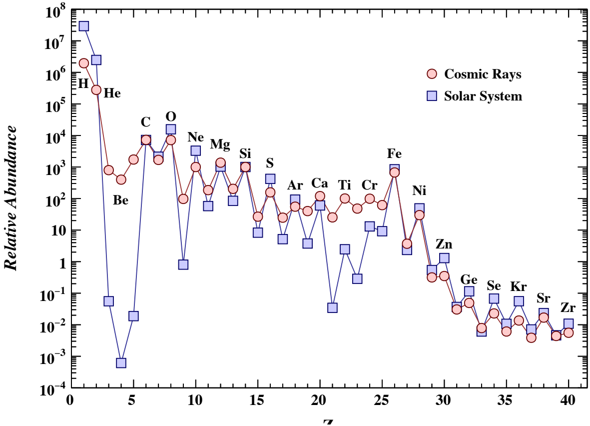
No antimatter domain can exist within the horizon!

– Cohen, De Rujula, Glashow 1997

Protons and Nuclei in cosmic rays



Aboundances: in cosmic rays vs. cosmological



Antiprotons in Cosmic Rays

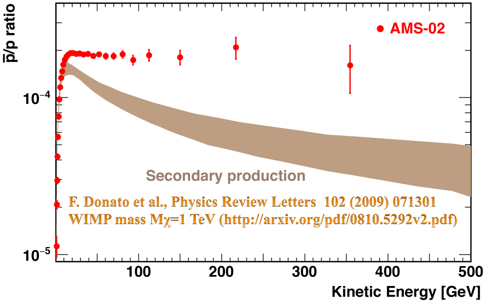
$\Phi_{\bar{p}}/\Phi_p \sim 10^{-4}$ AMS-02

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?)

$M_X \sim$ few hundred GeV

Anti-deuteron test?



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

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

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

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 ...

- There are dark stars (composed of DM) in the Universe

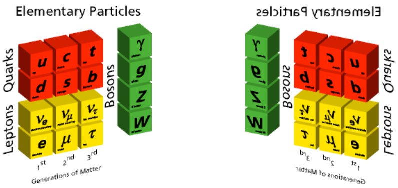
- They contain small antimatter eggs in their interiors (compressed by dark star gravity) – observable as a small antistar inside (invisible) dark star

- Gravitational mergers of dark stars "liberate" antimatter from their cores so producing anti-nuclei in cosmic rays

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

$G \times G'$

Regular world — Mirror world



- Two identical gauge factors, e.g. $SU(5) \times SU(5)'$, with identical field contents and Lagrangians: $\mathcal{L}_{\rm tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\rm mix}$
- Mirror sector ($\mathcal{L}'$) is dark – or perhaps grey? ($\mathcal{L}_{\rm mix} \;\to\;$ 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

fermions and anti-fermions :

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

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

$\updownarrow$ CP

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

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: $F_L \to F_R^c \equiv \bar{F}_R = C\overline{F_L}^T = C\gamma_0(F_L)^*$ 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

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

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

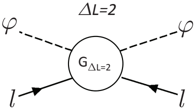
B$-$L is conserved also by non-perturbative effects

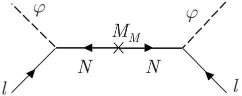
B$-$L breaking needs New Physics

B-L violation: Majorana masses of neutrinos

- $\frac{A}{M}(\ell\phi)(\ell\phi) \quad (\Delta L = 2)$
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

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

Two possible parities: with and without chirality change

fermions and anti-fermions :

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

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

$\updownarrow$ CP

$$\bar q_R=\begin{pmatrix}\bar u_R\\ \bar d_R\end{pmatrix},\quad \bar\ell_R=\begin{pmatrix}\bar\nu_R\\ \bar e_R\end{pmatrix};\qquad \bar u_L,\ \bar d_L,\qquad \bar e_L$$

B=–1/3 L=–1 B=–1/3 L=–1

Mirror fermions and antifermions :

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

B′=1/3 L′=1 B′=1/3 L′=1

$\updownarrow$ CP

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

B′=-1/3 L′=-1 B′=-1/3 L′=-1

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

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

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

– Sign of mirror baryon asymmetry ?

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

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

Imagine a baryogenesis mechanism *separately* acting in O and M sectors!
– without involving cross-interactions in $\mathcal{L}_{\rm mix}$
E.g. leptogenesis $N \to \ell\phi$ and $N' \to \ell'\phi'$

Z_2: $\to Y'_{u,d,e} = Y_{u,d,e}$ i.e. $\mathcal{B}' = 1$
– O and M sectors are CP-identical in same chiral basis O=left, M=left

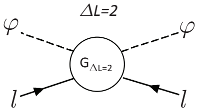
Z_2^{LR}: $\to Y'_{u,d,e} = Y^*_{u,d,e}$ i.e. $\mathcal{B}' = -1$
– O sector in L-basis is identical to M sector in R-basis O=left, M=right

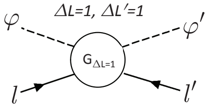
In the absence of cross-interactions in $\mathcal{L}_{\rm mix}$ we cannot measure sign of BA (or chirality in weak interactions) in M sector – so all remains academic ...

But switching on cross-interactions, violating B/L & B′/-L′ – as mixings
neutron–neutron′ $\epsilon n n' + \mathrm{h.c.}$ $\Delta(B-B') = 0$ or $\nu\nu' + \mathrm{h.c.}$ $\Delta(L-L') = 0$
$\mathcal{B}' = -1 \quad \to \quad \bar{n}' \to n$ M (anti)matter → O matter but $\bar{\nu}' \to \bar{\nu}$
$\mathcal{B}' = 1 \quad \to \quad n' \to \bar{n}$ M matter → O antimatter but $\nu' \to \nu$

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

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





- 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 $\frac{B}{M}(\ell\phi)(I\ell'\phi')$

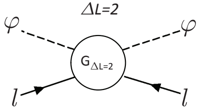
Akhmedov, ZB, Senjanovic 1992; Silagadze 1995

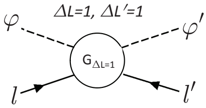
ZB and Mohapatra, 1995, Foot and Volkas 1995

Mirror neutrinos as most natural candidates for sterile neutrinos – they are light by the same reasons as normal neutrinos, and mixing is naturally large: $m'_\nu/m_\nu = (v'/v)^2$, $\tan 2\theta_{\nu\nu'} = v/v'$

$\nu - \nu'$ mixing and co-leptogenesis between O and M worlds

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





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

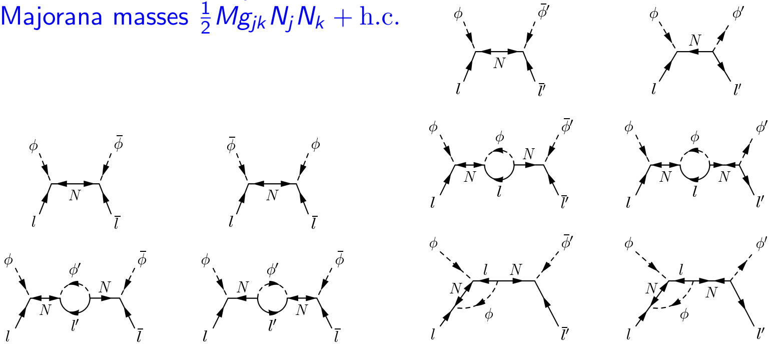
Celebrated conditions of Sakharov + Kuzmin Rubakov Shaposhnikov

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



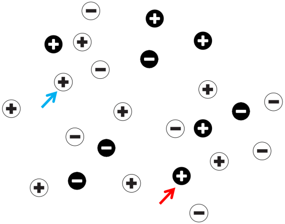
Complex Yukawa couplings $Y_{ij}l_iN_j\bar{\phi} + Y'_{ij}l'_iN_j\bar{\phi}' + \mathrm{h.c.}$

Z_2 (Xerox) symmetry $\to$ $Y' = Y$,
Z_2^{LR} (Mirror) symmetry $\to$ $Y' = Y^*$

Co-leptogenesis: Sign of Mirror BA

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

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

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

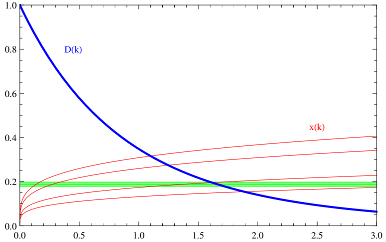
$$\Omega'_B = \Omega_B \simeq 10^3 \frac{J M_{Pl} T_R^3}{M^4} \simeq 10^3 J \left(\frac{T_R}{10^{11}\ {\rm GeV}}\right)^3 \left(\frac{10^{13}\ {\rm GeV}}{M}\right)^4$$

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

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

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

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.

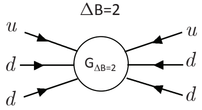
So we obtain $\Omega'_B = 5\Omega_B$ when $m'_B = m_B$ but $n'_B \simeq 5n_B$
– the reason: mirror world is colder

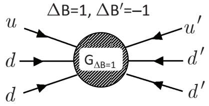
Alternative: $n'_B \simeq n_B$ but $m'_B \simeq 5m_B$ – if mirror parity is broken and $v'/v \sim 10^2$ (case of Little Higgs)

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

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

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





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

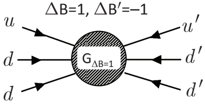
Exp. bounds on $n - \bar{n}$ oscillation $\quad \tau = \varepsilon^{-1}$ –oscillation time

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

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

Neutron – mirror neutron mixing

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



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

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 $\epsilon^{-1} = \tau_{nn'} \sim 1$ 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

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 ....

$n \to \bar{n}'$ 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

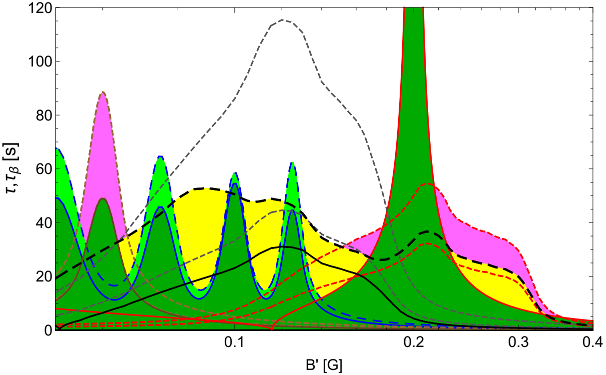
- Reactors and Spallation Facilities (experiments are looking for)
- In Cosmic Rays ($n - n'$ in TA and Auger experiments)
- During BBN epoch (fast $n' \to \bar{n}$ can solve Lithium problem)

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

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

Experiments

By now $\sim$ 15 different experiments were done at ILL/PSI/ORNL

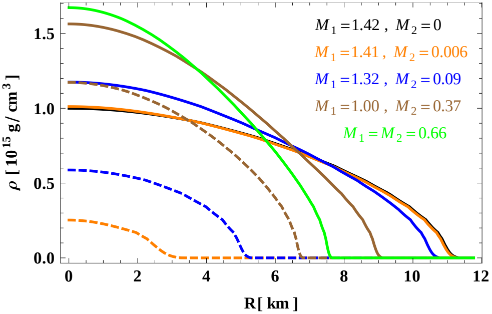


Several new experiments are underway at PSI, ILL and ORNL and are planned at ESS

Neutron Star transformation by $n - n'$ conversion

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

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



ZB, Biondi, Mannarelli, Tonelli, arXiv: 2012.15233

Neutron Stars: $n - n'$ conversion

Two states, n and n'

$$H = \begin{pmatrix} E(n_b) & \varepsilon \\ \varepsilon & E'(n_{b'}) \end{pmatrix}$$

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

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

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

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

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

for $t = 10^{10}$ yr, $\tau_\epsilon = 10^{15}$ yr gives M fraction 10^{-5}

$\sim 10^{52}$ nucleons – few Earth mass

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

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

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

$$T_{\mu\nu} = T^1_{\mu\nu} + T^2_{\mu\nu} = \mathrm{diag}(\rho g_{tt}, p g_{rr}, pr^2, pr^2 \sin^2\theta)$$

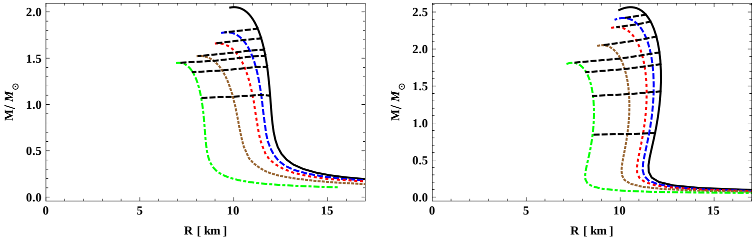
$$\rho = \rho_1 + \rho_2 \ \&\ p = p_1 + p_2, \qquad p_\alpha = F(\rho_\alpha)$$

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

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

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

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



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

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

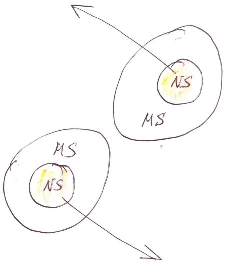
Such transitions in mirror NS create O matter cores. If baryon asymmetry in M sector has opposite sign, transitions $\bar{n}' \to \bar{n}$ create antimatter cores which can be seen by LAT by accreting ordinary gas and explain the origin of anti-helium nuclei in cosmic rays supposedly seen by AMS2

Mergers of NS .. and mirror NS

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

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

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 ... ZB, arXiv: 2106.11203

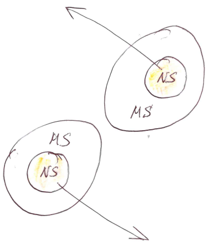
- DM from a hidden gauge sector having physics ∼ to ordinary matter:

SM × SM′ $e, p, n, \nu .. \leftrightarrow e', p', n', \nu'$ $SU(5) \times SU(5)', \ldots$ $E_8 \times E_8'$

- 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 $v \sim c$
- $\Phi_{\bar{b}} \sim R(\mathrm{NS'}-\mathrm{NS'}) \times N_{\bar{b}}^{\mathrm{NS}} \times \tau_{\mathrm{surv}} \times c \sim ??$ $\tau_{\mathrm{surv}} < 14$ 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

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

Antinuclei in Cosmic Rays ... AMS-02

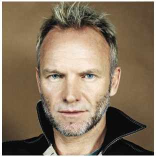
6 helium-3 and 2 helium-4 with energies $\sim$ GeV

$\Phi(\overline{\mathrm{He}})/\Phi(\mathrm{He}) \sim 10^{-8}$ – 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

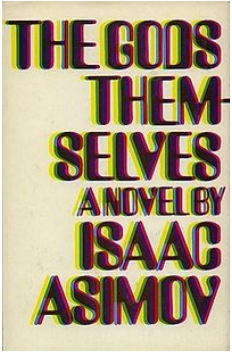
dark neutrons, before they decay, can be effectively transformed into our antineutrons in controllable way, by tuning vacuum and magnetic fields, if $\tau_{n\bar{n}'} < 10^3$ s

$E = 2m_n c^2 = 3 \times 10^{-3}$ 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 ...

Backup

Some auxiliary slides

Looking for antimatter stars/planets

DUPOURQUÉ, TIBALDO, and VON BALLMOOS PHYS. REV. D **103,** 083016 (2021)

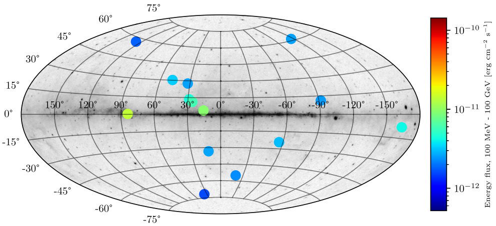


FIG. 1. Positions and energy flux in the 100 MeV–100 GeV range of antistar candidates selected in 4FGL-DR2. Galactic coordinates. The background image shows the *Fermi* 5-year all-sky photon counts above 1 GeV (image credit: NASA/DOE/Fermi LAT Collaboration).

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

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

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

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

Visible vs. Dark matter: $\Omega_D/\Omega_B \sim 1$?

Visible matter from Baryogenesis

B $(B-L)$ & CP violation, Out-of-Equilibrium

$\rho_B = n_B m_B$, $m_B \simeq 1$ 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.

- Sakharov 1967

Dark matter: $\rho_D = n_X m_X$, 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	$m_a \sim 10^{-5}$ eV $\quad n_a \sim 10^4 n_\gamma$ - CDM
Neutrinos	$m_\nu \sim 10^{-1}$ eV $\quad n_\nu \sim n_\gamma$ - HDM $(\times)$
Sterile ν'	$m_{\nu'} \sim 10$ keV $\quad n_{\nu'} \sim 10^{-3} n_\nu$ - WDM
Mirror baryons	$m_{B'} \sim 1$ GeV $\quad n_{B'} \sim n_B$ - ???
WIMP	$m_X \sim 1$ TeV $\quad n_X \sim 10^{-3} n_B$ - CDM
WimpZilla	$m_X \sim 10^{14}$ GeV $\quad n_X \sim 10^{-14} n_B$ - CDM

Quick overview of mirror dark matter ...

Parallel/mirror sector of particles as a duplicate of our SM: SM $\times$ SM$'$
(or $SU(5) \times SU(5)'$ or $E_8 \times E_8'$ or parallel branes ... or more sectors)
– all our particles (e, p, n, ν, γ...) have dark M twins (e', p', n', ν', γ'...) of exactly (or almost) the same masses

M matter is viable DM (asymmetric/baryonic/atomic/self-interacting/dissipative etc. as ordinary (O) baryon matter) – but M sector must be colder than O sector: $T'/T < 0.2$ or so (BBN, CMB, LSS etc.)
– asymmetric reheating between the two sectors after inflation

– O matter mainly hydrogen (H 75%, ^{4}He 25%)
while M matter mostly helium (H$'$ 25%, ^{4}He$'$ 75%) – first M stars are formed earlier than O stars, are bigger, helium dominated and end up in heavy BH: $M \sim (10 \div 10^2)\, M_\odot$ (inferring $\sim 80\%$ of DM in galactic halo and for the rest of $\sim 20\%$ – M gas clouds, $\sim M_\odot$ stars etc.

There can exist interactions between O and M particles, e.g. photon kinetic mixing $\varepsilon F^{\mu\nu} F'_{\mu\nu}$, some common gauge bosons, etc.
Most interesting are the ones which violate baryon and lepton numbers between two sectors, and namely $B - L$ and $B' - L'$ which can co-generate baryon asymmetries in both sectors – and naturally explain why the DM and baryon fractions are comparable, $\Omega_{B'}/\Omega_B \simeq 5$ or so