On the origin of antimatter in cosmos

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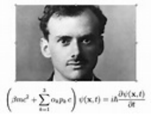
Contents

Anti-particles and anti-matter (antinulei)

From discovery of positron, 1930-32

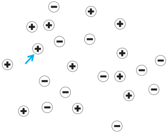
and all other antiparticles (antiproton, antineutron etc.)



... 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

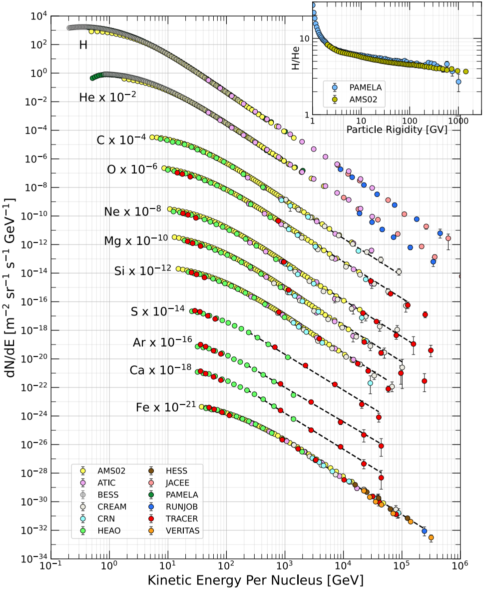
There should be no antimatter in the Universe!

In any case, matter should dominate the entire visible Universe

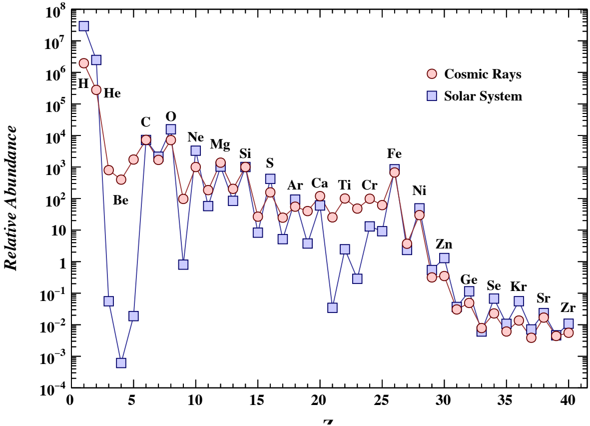
No antimatter domain can exist within the horizon!

– Cohen, De Rujula, Glashow 1997

Particles in cosmic rays



Aboundances: in cosmic rays vs. cosmological

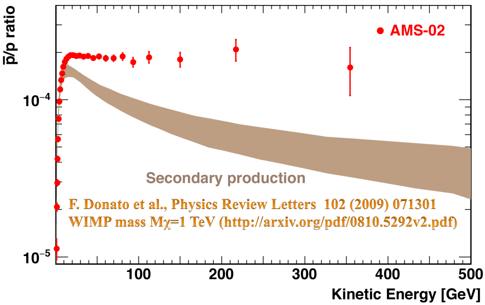


Indirect detection: antiparticles in the cosmic rays?

$\Phi_{\bar{p}}/\Phi_p \sim 10^{-4}$ 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 annihilation into proton + antiproton ?
(electron + positron?) $M_X \sim$ few hundred GeV
Anti-deuteron test? Donato, Fornengo, Maurin, 2008



Antinuclei in cosmic rays ...

But 8 anti-helium candidates were observed by AMS-02:

$\Phi(\overline{\mathrm{He}})/\Phi(\mathrm{He}) \sim 10^{-8}$ 6 helium-3 and 2 helium-4

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

The discovery of a single antihelium-4 nucleus is challenging to all known physics.

If true, this should be strong indication to non-trivial new physics

Some *specifically tuned* DM models could explain the flux of antihelium-3 – but they fail to explain antihelium-4 !

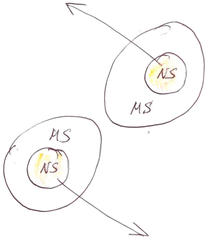
Ting promised that AMS-02 will publish the anti-nuclei data as soon as they see first sl anti-carbon

My hypothesis ...

- we observed neutron stars (NS) and NS-NS gravitational mergers:
  merger rate $R \sim (10^2 \div 10^3)\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
- there can exist dark neutron stars (NS′) built of mirror neutrons n'
- the neutron–mirror neutron mixing induces $n' \to \bar{n}$ transition

– antimatter "eggs" grow inside NS′ $\quad N_{\bar{b}} \sim 10^{57} \cdot t_{\mathrm{NS}}/\tau_{nn'}$

- in NS′-NS′ mergers the anti-nuclei are "liberated" with $v \sim c$
- $\Phi_{\bar{b}} \sim R\, N_{\bar{b}}\, \tau_{\mathrm{surv}}\, c \sim \left(\frac{R}{10^3\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}}\right)\left(\frac{N_{\bar{b}}}{10^{53}}\right)\left(\frac{\tau_{\mathrm{surv}}}{10^{17}\ \mathrm{s}}\right) \times 10^{-6}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  $\tau_{\mathrm{surv}} = (n_p \langle \sigma_{\mathrm{ann}} v \rangle)^{-1} \simeq 10^{14} \times (1\ \mathrm{cm}^{-3}/n_p)$



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 $U(1)_L$

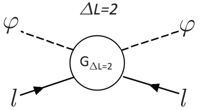
B$-$L is conserved also by non-perturbative effects

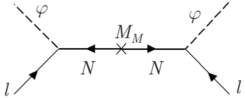
B$-$L breaking needs New Physics

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

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 $m_X = ?$, $n_X = ?$

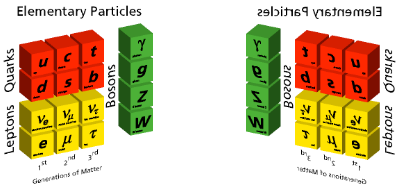
n_X is model dependent: DM particle mass and interaction strength (production and annihilation cross sections), freezing conditions, etc.

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

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

$$G \times G'$$

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 (Z_2 or Z_2^{LR}): no new parameters in $\mathcal{L}'$
- Cross-interactions between O & M particles
  $\mathcal{L}_{mix}$: new operators – new parameters! limited only by experiment!

$SU(3)\times SU(2)\times U(1)$ 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. EW baryogenesis or 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 and B′ – as neutron–mirror neutron mixing: $\epsilon n' n + \mathrm{h.c.}$ or $\nu - \nu'$ mixing

$\mathcal{B}' = -1 \quad \to \quad \bar{n}' \to n$ 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 $\nu' \to \nu$

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

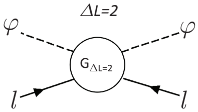
M matter is viable DM (asymmetric/baryonic/atomic/self-interacting/dissipative etc. as ordinary (O) baryon matter) – but M sector must be colder than O sector: $T'/T < 0.2$ or so (BBN, CMB, LSS etc.)
– asymmetric reheating between the two sectors after inflation

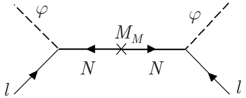
– O matter mainly hydrogen (H 75%, ^{4}He 25%)
while M matter mostly helium (H$'$ 25%, ^{4}He$'$ 75%) – first M stars are formed earlier than O stars, are bigger, helium dominated and end up in heavy BH: $M \sim (10 \div 10^2)\, M_\odot$ (inferring $\sim 80\%$ of DM in galactic halo and for the rest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

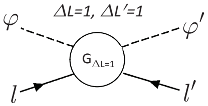
B-L violation in O and M sectors: Active-sterile mixing

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



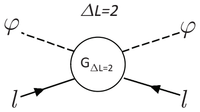


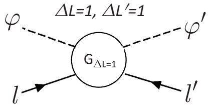
- Neutrino -mirror neutrino mixing – (active - sterile mixing)
L and L' violation: $\frac{A}{M}(\ell\phi)(\ell\phi)$, $\frac{A}{M}(\ell'\phi')(\ell'\phi')$ and $\frac{B}{M}(\ell\phi)(l\ell'\phi')$



Mirror neutrinos as natural candidates for sterile neutrinos
ZB and Mohapatra 95, ZB, Dolgov and Mohapatra 96

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





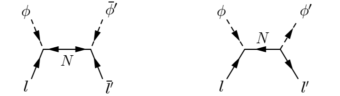
After inflation, our world is heated and mirror world is empty: but ordinary particle scatterings transform them into mirror particles, heating also mirror world.

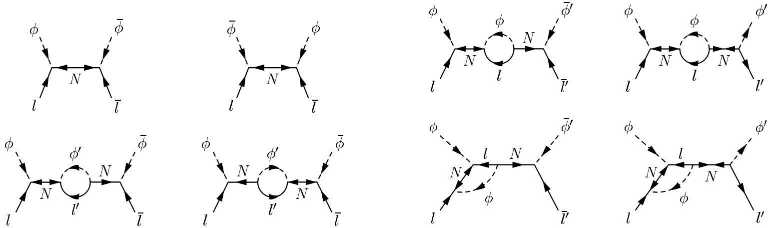
- These processes should be out-of-equilibrium
- Violate baryon numbers in both worlds, $B - L$ and $B' - L'$
- Violate also CP, given complex couplings

Green light to celebrated conditions of Sakharov

Co-leptogenesis: Z.B. and Bento, PRL 87, 231304 (2001)

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





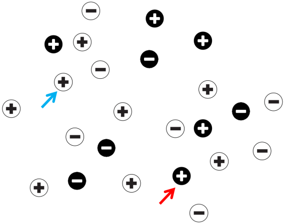
Complex Yukawa couplings $Y_{ij}l_iN_j\bar{\phi} + Y'_{ij}l'_iN_j\bar{\phi}' + \mathrm{h.c.}$

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 $\longrightarrow$ *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}): $Y' = Y^* \quad \to \quad \Delta\sigma' = -\Delta\sigma \quad \to \quad B > 0,\ B' > 0$

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

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

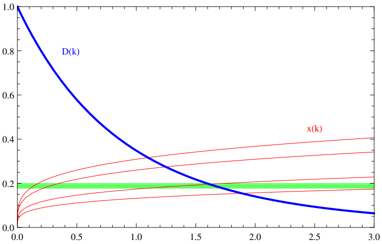
$$\Omega'_B = \Omega_B \simeq 10^3 \frac{J M_{Pl} T_R^3}{M^4} \simeq 10^3 J \left(\frac{T_R}{10^{11}\ {\rm GeV}}\right)^3 \left(\frac{10^{13}\ {\rm GeV}}{M}\right)^4$$

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 $n'_B = 5n_B$
– the reason: mirror world is colder

Now the neutrons: since 1932 they make 50% of mass in our bodies ...

Neutrons are closely mass degenerate with the proton (in the SM $n = udd$, $p = uud$) since B is conserved in the SM, n and p both are Dirac particles with $B = 1$)

Neutrons are stable in basic nuclei but decay in free state: $n \to pe\bar{\nu}_e$
... and decay also in some (β^- unstable) nuclei
... and can be even born in other (β^+ unstable) nuclei: $p \to ne^+\nu_e$

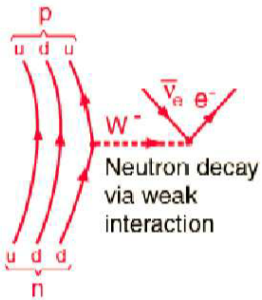
Fermi V-A Theory $\to$ *Standard Model*

$$\frac{G_V}{\sqrt{2}}\ \overline{u}(1-\gamma^5)\gamma^\mu d\ \ \overline{\nu}_e(1-\gamma^5)\gamma_\mu e \quad + \text{h.c.}$$

$$G_V = G_F\,|V_{ud}|$$

$$\frac{G_V}{\sqrt{2}}\ \overline{p}(g_V - g_A\gamma^5)\gamma^\mu n\ \ \overline{\nu}_e(1-\gamma^5)\gamma_\mu e \quad + \text{h.c.}$$

$$g_V = 1 \text{ (CVC)} \quad \& \quad g_A \simeq 1.2 \text{ (PCAC)}$$

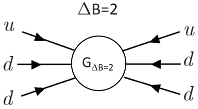


Yet, we do not know all its secrets in depth ...

Majorana mass of the neutron $= n - \bar{n}$ mixing

Neutron is a Dirac particle: $m\,\overline{n}\,n \quad (\Delta B = 0)$ with $m \simeq 1$ GeV

In principle, being neutral, it could have also a Majorana mass
$\epsilon(n^T C n + \bar{n}^T C \bar{n})$ $(\Delta B = 2)$ even with ϵ larger than m
But being composite, this Majorana mass can come only from
six-fermions effective operator $\frac{1}{M^5}(udd)(udd)$, $M > 1$ TeV or so



$$\varepsilon = \langle n|(udd)(udd)|\bar{n}\rangle \sim \frac{\Lambda^6_{\rm QCD}}{M^5} \sim \left(\frac{10~\rm TeV}{M}\right)^5 \times 10^{-15}~\text{eV}~~(\text{or} \sim 1~\rm s^{-1})$$

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

$M > 10$ TeV $\to$ $\varepsilon < 10^{-15}$ eV $\to$ $\tau_{n\bar{n}} > 1$ s
$M \sim 10^3$ TeV $\to$ $\varepsilon \sim 10^{-25}$ eV $\to$ $\tau_{n\bar{n}} \sim 10^{10}$ s

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

$n - \bar{n}$ oscillation: Free (and bound)

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

$$H = \begin{pmatrix} m + \mu \vec{B}\vec{\sigma} - V_n & \epsilon \\ \epsilon & m - \mu \vec{B}\vec{\sigma} - V_{\bar{n}} \end{pmatrix}$$

Free oscillation probability $P_{n\bar{n}}(t) = \frac{\epsilon^2}{\omega_B^2} \sin^2(\omega_B t), \quad \epsilon \ll \omega_B = \mu B$

$\omega_B t < 1 \;\; \rightarrow \;\; P_{n\bar{n}}(t) = (\epsilon t)^2 = (t/\tau_{n\bar{n}})^2$

$\omega_B t \gg 1 \;\; \rightarrow \;\; P_{n\bar{n}}(t) = \frac{1}{2}(\epsilon/\omega_B)^2 < \frac{(\epsilon t)^2}{(\omega_B t)^2}$

for a given free flight time t, magn. field should be properly suppressed to achieve "quasi-free" regime: $\omega_B t < 1$

Baldo-Ceolin et al, 1994 (ILL, Grenoble) : $t \simeq 0.1$ s, $\quad B < 1$ mG

$P_{n\bar{n}}(t) = (t/\tau_{n\bar{n}})^2 < 10^{-18} \quad \longrightarrow \quad \epsilon < 7.7 \times 10^{-24}$ eV

In nuclei: $\Delta V = V_{\bar{n}} - V_n \sim 100$ MeV $\quad \theta \simeq \epsilon/\Delta V < 10^{-23}$
$P_{n\bar{n}} \simeq \theta^2 \simeq (\epsilon/\Delta V)^2 < 10^{-46}$ – is unobservable? Not really ...

$n - \bar{n}$ mixing and instability of matter (nuclei)

In principle, $n - \bar{n}$ oscillation could be rather fast:
E.g. for $M \sim 10$ TeV (otherwise safe scale for new physics)
one would have $\tau_{n\bar{n}} \sim 1$ s $\quad \to \quad P_{n\bar{n}}(t = 0.1\,\mathrm{s}) \simeq (t/\tau_{n\bar{n}})^2 \simeq 10^{-4}$

However: *$n - \bar{n}$ 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 $\quad \to \quad \tau > 1.3 \times 10^{8}$ s $\quad$ Fe, Soudan 2002
$\varepsilon < 2.5 \times 10^{-24}$ eV $\quad \to \quad \tau > 2.7 \times 10^{8}$ s $\quad$ O, SK 2015

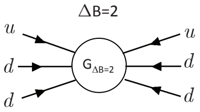
$\varepsilon < 7.5 \times 10^{-24}$ eV $\quad \to \quad \tau > 0.86 \times 10^{8}$ s $\quad$ direct limit free n

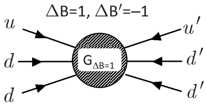
B violating operators between O and M particles in $\mathcal{L}_{\rm mix}$

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)

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

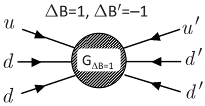




Oscillations $n \to \bar{n}$ $(\Delta B = 2)$
Oscillations $n \to \bar{n}'$ $(\Delta B = 1,\ \Delta B' = 1)$ $B - B'$ is conserved

Neutron – 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 $\quad B - B'$



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

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 ($n - n'$ can reconcile 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 $n - n'$

Neutron Stars: $n - n'$ conversion

Two states, n and n'

$$H = \begin{pmatrix} m_n + V_n + \mu_n \vec{B}\vec{\sigma} & \varepsilon \\ \varepsilon & m'_n + V'_n - \mu_n \vec{B}'\vec{\sigma} \end{pmatrix}$$

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

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.

$\tau_\epsilon = \Gamma^{-1} = \epsilon_{15}^{-2} \left(\frac{M}{1.5\, M_\odot} \right)^{2/3} \times 10^{15}$ yr $N'/N_0 = t/\tau_\epsilon$

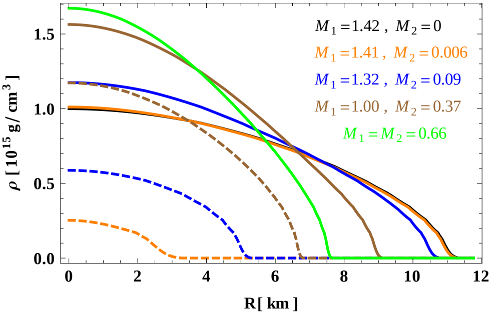
for $t = 10$ Gyr, $\tau_\epsilon = 10^{15}$ yr gives M fraction 10^{-5} – few Earth mass

$\dot{\mathcal{E}} = \frac{E_F N}{\tau_\epsilon} = \left(\frac{10^{15}\,\mathrm{yr}}{\tau_\epsilon} \right) \left(\frac{M}{1.5\, M_\odot} \right) \times 10^{31}$ erg/s NS heating – surface T

Neutron Star transformation

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

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



Quark stars: in strange quark matter (color-superconducting phase) transition is not energetically farored. So Quark stars (which perhaps are heavy pulsars with $M \simeq 2\, M_\odot$ or so) are insensitive to $n \to n'$.

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

On the origin of antimatter in cosmos

Zurab Berezhiani

Summary

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

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

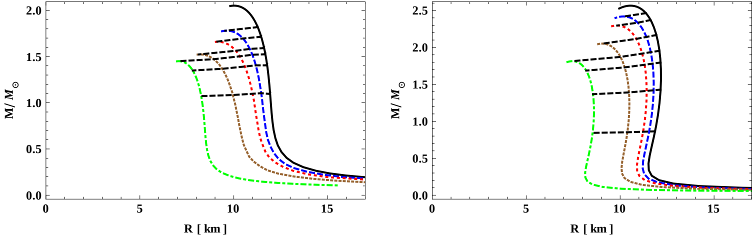
$$\rho = \rho_1 + \rho_2 \ \&\ p = p_1 + p_2, \qquad p_\alpha = F(\rho_\alpha)$$

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

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

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

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



$\sqrt{2}$ 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

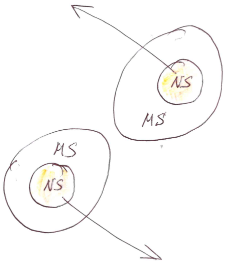
Such transitions in mirror NS create O matter cores. If baryon asymmetry in M sector has opposite sign, transitions $\bar{n}' \to \bar{n}$ create antimatter cores which can be seen by LAT by accreting ordinary gas and explain the origin of anti-helium nuclei in cosmic rays supposedly seen by AMS2

Mergers of neutron stars .. and mirror neutron stars

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



Looking for antimatter stars/planets

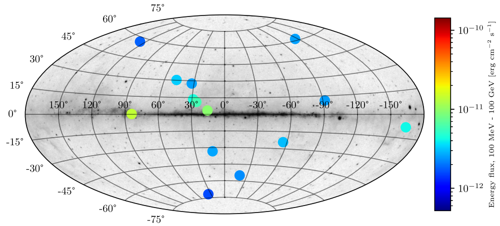


FIG. 1. Positions and energy flux in the 100 MeV–100 GeV range of antistar candidates selected in 4FGL-DR2. Galactic coordinates. The background image shows the *Fermi* 5-year all-sky photon counts above 1 GeV (image credit: NASA/DOE/Fermi LAT Collaboration).

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

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

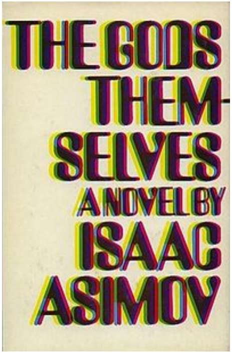
dark neutrons, before they decay, can be effectively transformed into our antineutrons in controllable way, by tuning vacuum and magnetic fields, if $\tau_{n\bar{n}'} < 10^3$ s

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

Neutron – mirror neutron oscillation probability

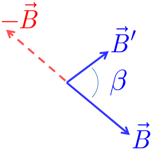
$$H = \begin{pmatrix} m + \mu\vec{B}\vec{\sigma} + V & \epsilon \\ \epsilon & m + \mu\vec{B}'\vec{\sigma} + V' \end{pmatrix}$$

The probability of n-n' transition depends on the relative orientation of magnetic and mirror-magnetic fields. The latter can exist if mirror matter is captured by the Earth

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

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

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



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

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

Earth mirror magnetic field via the electron drag mechanism

Earth can accumulate some, even tiny amount of mirror matter due to Rutherford-like scattering of mirror matter due to photon-mirror photon kinetic mixing.

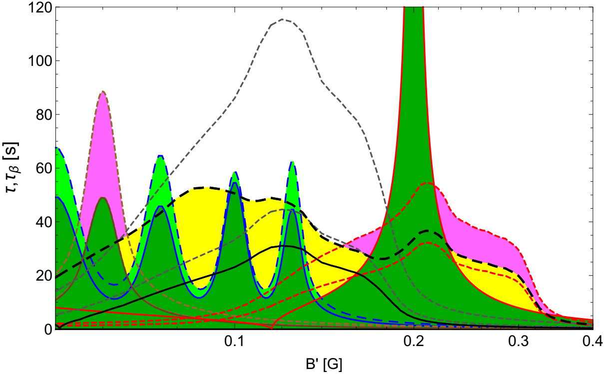
High temperature of the Earth core $\to$ mirror gas is partially ionized.

Rotation of the Earth drags mirror electrons but cannot move as well mirror ions which are much heavier. So circular electric currents can emerge which seed the mirror magnetic field. Rather tiny amount of captured mirror matter (say $\sim 10^{45}$ particles) would suffice

These seeds can be strongly enhanced by the dynamo mechanism: mirror plasma captured in the Earth must differentially rotate and also have convective motions

Experiments

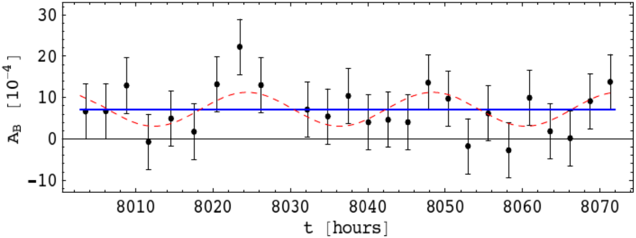
By now 8 experiments were done at ILL/PSI



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

2009 – magnetic field vertical

Experiment sequence: $\{B_-, B_+, B_+, B_-, B_+, B_-, B_-, B_+\}$,
$B \simeq 0.2G$



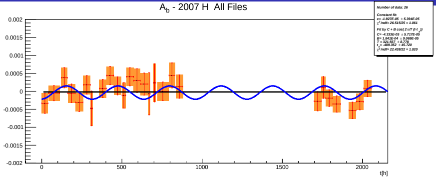
Careful analysis has shown the non-zero effect: Z.B. and Nesti, 2012

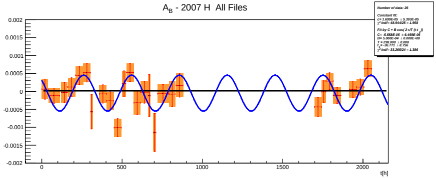
$$A(B) = (7.0 \pm 1.3) \times 10^{-4} \qquad \chi^2_{/dof} = 0.9 \longrightarrow 5.2\sigma$$

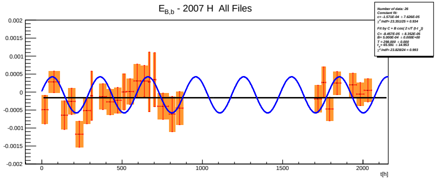
Modulation with the period $T = 24$ hour $\longrightarrow 5.5\sigma$

2009 – magnetic field Horizontal

large field $B_\pm = 0.2$ G and small field $b_\pm < 10^{-2}$ G

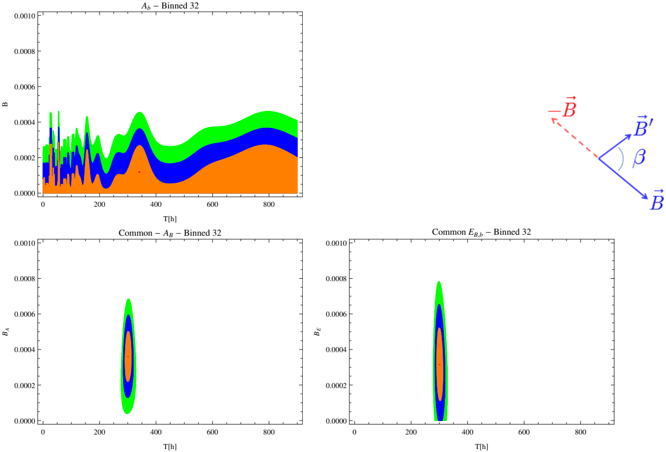






2009 – magnetic field Horizontal

large field $B = 0.2$ G and small field $b < 10^{-2}$ G



small field: $A_b \simeq 0$, but large field measurements show non-zero A_B and E_B, both with the period $T \simeq 300$ hours
(Unpublished and not included in Fig. of exp. limits)

Can neutron be transformed into antineutron ... effectively?

Small Majorana mass of neutron $\frac{\epsilon}{2}\left(n^T C n + \overline{n} C \overline{n}^T\right) = \frac{\epsilon}{2}\left(\overline{n_c}\, n + \overline{n}\, n_c\right)$
$\equiv \quad n - \bar{n}$ oscillation $\quad (\Delta B = 2)$

Oscillation probability for free flight time t
$P_{n\bar{n}}(t) = (\epsilon\, t)^2 = (t/\tau_{n\bar{n}})^2$ in quasi-free regime $\omega_B t < 1$

Present bounds on oscillation time $\tau_{n\bar{n}} = \epsilon^{-1}$ are severe:
$\tau_{n\bar{n}} > 0.86 \times 10^8$ s direct limit (free n) ILL, 1994
$\tau_{n\bar{n}} > 2.7 \times 10^8$ s nuclear stability (bound n) SK, 2020 (this conf.)

$$P_{n\bar{n}}(t) = \frac{t^2}{\tau_{n\bar{n}}^2} = \left(\frac{10^8 \text{ s}}{\tau_{n\bar{n}}}\right)^2 \left(\frac{t}{0.1 \text{ s}}\right)^2 \times 10^{-18}$$

Shortcut through mirror world: $n \to n' \to \bar{n}$:
Experimental search to be tuned against (dark) environmental conditions

$$P_{n\bar{n}}(t) = P_{nn'}(t) P_{n\bar{n}'}(t) = \frac{t^4}{\tau_{nn'}^2 \tau_{n\bar{n}'}^2} = \left(\frac{1 \text{ s}^2}{\tau_{nn'}\tau_{n\bar{n}'}}\right)^2 \left(\frac{t}{0.1 \text{ s}}\right)^4 \times 10^{-4}$$

No danger for nuclear stability !

Nor for Neutron Stars

$2 \times 2 = 4$!

Z.B., Eur.Phys.J C81:33 (2021), arXiv:2002.05609

4 states: $n,\ \bar{n}\ :\ n',\ \bar{n}'$ and mixing combinations:

$$n \longleftrightarrow \bar{n} \quad (\Delta B = 2) \qquad \& \qquad n' \longleftrightarrow \bar{n}' \quad (\Delta B' = 2)$$

$$n \longleftrightarrow n' \quad + \quad \bar{n}' \longleftrightarrow \bar{n} \qquad \Delta(B - B') = 0$$

$$n \longleftrightarrow \bar{n}' \quad + \quad n' \longleftrightarrow \bar{n} \qquad \Delta(B + B') = 0$$

Full Hamiltonian is 8×8:

$$\begin{pmatrix} m_n + \mu \vec{B}\vec{\sigma} & \epsilon_{n\bar{n}} & \epsilon_{nn'} & \epsilon_{n\bar{n}'} \\ \epsilon_{n\bar{n}} & m_n - \mu \vec{B}\vec{\sigma} & \epsilon_{n\bar{n}'} & \epsilon_{nn'} \\ \epsilon_{nn'} & \epsilon_{n\bar{n}'} & m'_n + V'_n + \mu' \vec{B}'\vec{\sigma} & \epsilon_{n\bar{n}} \\ \epsilon_{n\bar{n}'} & \epsilon_{nn'} & \epsilon_{n\bar{n}} & m'_n + V'_n - \mu' \vec{B}'\vec{\sigma} \end{pmatrix}$$

Present bounds on oscillation time $\tau_{n\bar{n}} = \epsilon^{-1}$:

$\tau_{n\bar{n}} > 0.86 \times 10^8$ s (free n), $\tau_{n\bar{n}} > 4.7 \times 10^8$ s (bound n)

$$P_{n\bar{n}}(t) = \frac{t^2}{\tau_{n\bar{n}}^2} = \left(\frac{10^8\ \mathrm{s}}{\tau_{n\bar{n}}}\right)^2 \left(\frac{t}{0.1\ \mathrm{s}}\right)^2 \times 10^{-18}$$

Shortcut for $n \to \bar{n}$ via $n \to n' \to \bar{n}$

Consider case when direct $n - \bar{n}$ mixing simply absent: $\epsilon_{n\bar{n}} = 0$

Anyway, $n \to \bar{n}$ emerges as second order effect via $n \to n'\bar{n}' \to \bar{n}$

$$\overline{P}_{n\bar{n}} = \overline{P}_{nn'} \overline{P}_{n\bar{n}'}$$

$$\overline{P}_{nn'} = \frac{2\epsilon^2_{nn'}\cos^2(\beta/2)}{(\Omega-\Omega')^2} + \frac{2\epsilon^2_{nn'}\sin^2(\beta/2)}{(\Omega+\Omega')^2}, \quad \overline{P}_{n\bar{n}'} = \frac{2\epsilon^2_{n\bar{n}'}\sin^2(\beta/2)}{(\Omega-\Omega')^2} + \frac{2\epsilon^2_{n\bar{n}'}\cos^2(\beta/2)}{(\Omega+\Omega')^2}$$

where β is the (unknown) angle between the vectors $\vec{B}$ and $\vec{B}'$

Disappearance experiments measure the sum $P_{nn'} + P_{n\bar{n}'} \propto \epsilon^2_{nn'} + \epsilon^2_{n\bar{n}'}$

$n - \bar{n}$ transition measures the product $P_{n\bar{n}} = P_{nn'} P_{n\bar{n}'} \propto \epsilon^2_{nn'}\epsilon^2_{n\bar{n}'}$
From the ILL'94 limit $P_{n\bar{n}} < 10^{-18}$ (measured at $B = 0$) we get

$$\tau_{nn'}\,\tau_{n\bar{n}'} > \frac{2\times 10^9}{\Omega'^2} \approx \left(\frac{0.5\,\mathrm{G}}{B'}\right)^2 \times 100\ \mathrm{s}^2$$

E.g. $\tau_{nn'}\,\tau_{n\bar{n}'} \sim 1$ second is possible if $B' \sim 5$ G
Limits become even weaker if $\Delta m > 0.1$ neV

How good the shortcut can be?

Assuming e.g. $\tau_{nn'}\,\tau_{n\bar{n}'} = 100$ s and $B' = 0.5$ G, we see that ILL94-like measurement at $B = 0.45$ G (or $B = 0.49$ G) would give $P_{n\bar{n}} \simeq \sin^2\beta \times 10^{-15}$ (or $P_{n\bar{n}} \simeq \sin^2\beta \times 10^{-12}$)

To maximalize $n - \bar{n}$ probability, one has to match resonance with about 1 mG precision: we get

$$P_{nn'}(t) = \left(\frac{t}{\tau_{nn'}}\right)^2 \cos^2\frac{\beta}{2}, \qquad P_{n\bar{n}'}(t) = \left(\frac{t}{\tau_{n\bar{n}'}}\right)^2 \sin^2\frac{\beta}{2}$$

and

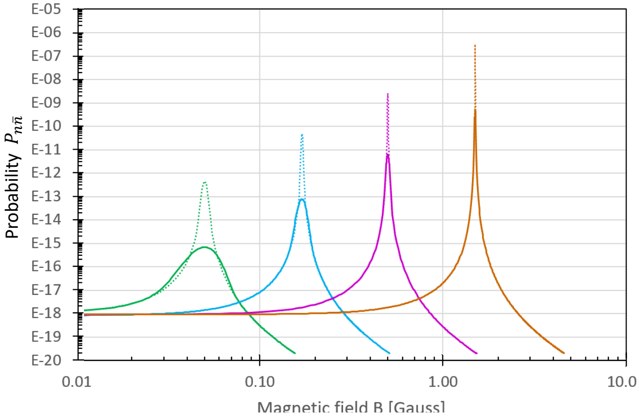
$$P_{n\bar{n}}(t) = P_{nn'}(t)P_{n\bar{n}'}(t) = \frac{\sin^2\beta}{4}\left(\frac{t}{0.1\ \mathrm{s}}\right)^4\left(\frac{100\ \mathrm{s}^2}{\tau_{nn'}\tau_{n\bar{n}'}}\right)^2 \times 10^{-8}$$

Practically no limit from nuclear stability

E.g. ^{16}O decay time predicted $\sim 10^{60}$ yr vs. present limit $\sim 10^{32}$ yr !

How effective $n \to \bar{n}$ can be?

simulations for $n - \bar{n}$ experiment with
$t = 0.1$ s ($\ell = 100$ m as ILL) and $t = 0.02$ s ($\ell = 20$ m)

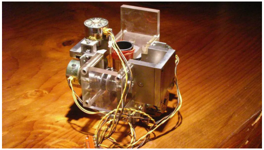


– and perhaps a chance for free energy ?

Majorana Machine

Che cretini! Hanno scoperto il protone neutro e non se ne accorgono!

La fisica è su una strada sbagliata. Siamo tutti su una strada sbagliata...



La fantomatica macchina forse teorizzata da Ettore Majorana! Nella sua formulazione attuale violerebbe un'infinità di principi scientifici, producendo enormi quantità di energia a costo zero. Non può affatto esistere ...

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The Universe: Anthrophic or Intelligent Design?

Is the Universe Anthropic? multiverse...

or Anthropomorphic? with basic instincts to survive

or Anthrophilic? has sapience and purposes ...

Conspiracy in the fine selection of the SM parameters:
M_W, $\Lambda_{\rm QCD}$, Yukawa constants $\theta_{\rm QCD}$?
and Cosmological term? (Weinberg's anthropic argument ...)
E.g. Neutron-proton-electron mass conspiracy: $m_e < m_n - m_p$
– neutron decays if free but is stable in nuclei with $E_b \sim$ few MeV

Taken Standard Model with all coupling constants fixed in UV, sort of "explanation" why $M_W \sim 10^2$ GeV

$M_W < 10$ GeV $\longrightarrow m_e > m_n - m_p$ hydrogen atom decays $pe \to n\nu$

$M_W > 10^3$ GeV $\longrightarrow m_n > m_p + m_e + E_b$ only hydrogen, no nuclei

– in either case, no life! And noone can ask stupid questions "Why?"

Anthropic limit on $n - \bar{n}$ mixing

Nuclear instability against
$(A, Z) \to (A-1, \bar{n}, Z) \to (A-2, Z/Z-1) + \pi$'s scales as
Scale of new physics unknown – but $\tau_{\rm nucl} \propto \epsilon^2 \propto 1/M^{10}$ $(\epsilon \propto 1/M^5)$

Present limit $\tau_{\rm nucl} > 10^{32}$ yr implies
$\epsilon < 2.5 \times 10^{-24}$ eV $\longrightarrow$ $M > 500$ TeV or so

$M \to M/3$ (just 3 times less) would give $\tau_{\rm nucl} \to \tau_{\rm nucl}/3^{10} \approx 10^{27}$ yr

$\bar{n}n$ $(\bar{n}p)$ annihilation releases energy $E_{\rm ann} = 2m_n c^2 \approx 3 \times 10^{-10}$ J

Then the Earth power $= E_{\rm ann} N_{\oplus}/\tau_{\rm nucl} \simeq 10$ TW
.. the Earth radioactivity turns dangerous for the Life!

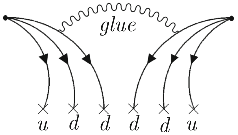
And (happily) the neutron is not elementary particle
– in which case it could have unsuppressed Majorana mass $\varepsilon n^T C n$
It is composite $n = (udd)$ of three quarks – Majorana mass
can be induced only by D=9 operator $\frac{1}{M^5}(udd)^2$
Life can exist because of the (intelligent) structure of the SM

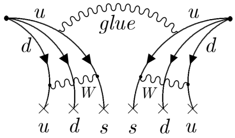
Disgression: Anthropic θ-term in QCD

Z.B., EPJ C 76, 705 (2016), arXiv:1507.05478

QCD forms quark condensate $\langle \overline{q}q\rangle \sim \Lambda^3_{\rm QCD}$ breaking chiral symmetry (and probably 4-quark condensates $\langle \overline{q}q\overline{q}q\rangle$ not reducible to $\langle \overline{q}q\rangle^2$)

Can six-quark condensates $\langle qqqqqq\rangle$ be formed? (i.e. 3 diquarks)
$\langle (udd)^2\rangle$ or $\langle (uds)^2\rangle$ inducing $n-\bar{n}$, $\Lambda-\overline{\Lambda}$ mixings ($\Delta B = 2$)





Vafa-Witten theorem: QCD cannot break vector symmetries ...
.. the prove relies on the absence of θ-term (valid strictly for $\theta = 0$)
Imagine then world with $\theta \sim 1$ where $\langle qqqqqq\rangle \sim \Lambda^9_{\rm QCD}$
– bad for Life: enormous $n-\bar{n}$ or $\Lambda-\overline{\Lambda}$ ...

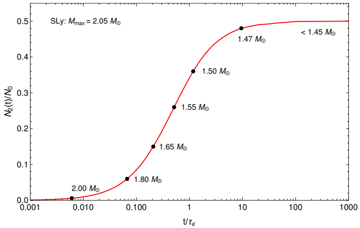
Let us assume $\langle qqqqqq\rangle_\theta \sim F(\theta)\,\Lambda^9_{\rm QCD}$ with $F(\theta)$ being a smooth periodic and even function: $F(\theta) \simeq \theta^2 + \ldots$
Then for $\theta \sim 10^{-10}$, $\langle qqqqqq\rangle_\theta = \theta^2\Lambda^9_{\rm QCD} \sim (1\ {\rm MeV})^9$
Then $\epsilon \sim \theta^2\Lambda^9_{\rm QCD}/m^8 \rightarrow \theta < 10^{-11}$ or so

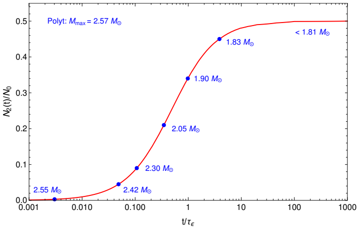
Neutron Stars Evolution to mixed star

$\tau_\epsilon = (10^{-15}\,\mathrm{eV}/\epsilon)^2 \times 10^{15}$ yr Two regimes are allowed :

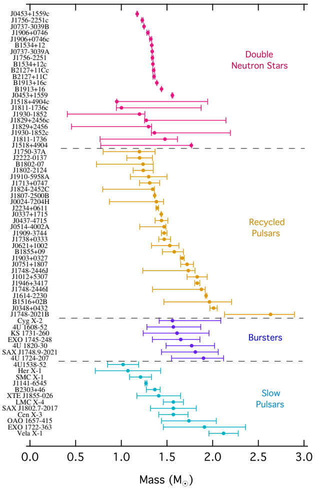
1. slow transformation ($\tau_\varepsilon \gg 14$ Gyr age of universe)
then limit from pulsar heating tells $\tau_\epsilon > 10^{15}$ yr $\longrightarrow$ $\epsilon < 10^{-15}$ eV or so
matches exp. limits for exactly degenerate $n - n'$

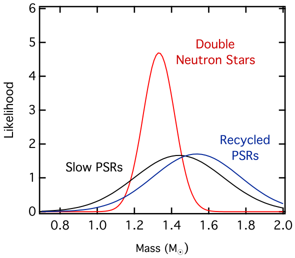
2. fast transformation $\tau_\epsilon < 10^5$ yr or so $\longrightarrow$ $\epsilon > 10^{-10}$ eV or so
– then old pulsars all should be transformed into maximally mixed stars
matches explanation of neutron lifetime anomaly, non-degenerate $n - n'$





Neutron Stars: mass distribution





Neutron Stars: observational $M - R$

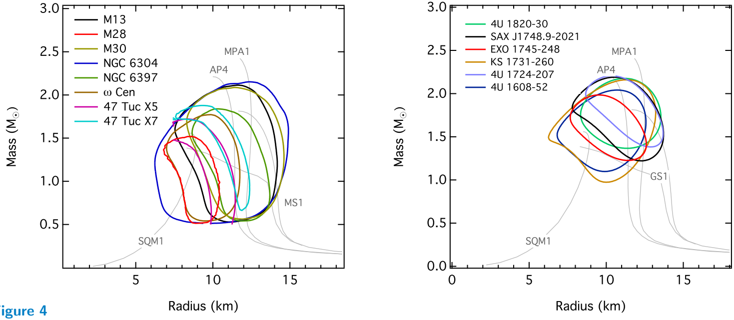
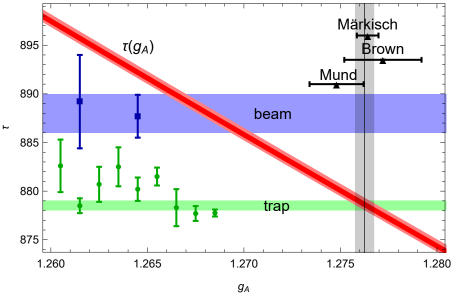


Figure 4

The combined constraints at the 68% confidence level over the neutron star mass and radius obtained from (Left) all neutron stars in low-mass X-ray binaries during quiescence (Right) all neutron stars with thermonuclear bursts. The light grey lines show mass-relations corresponding to a few representative equations of state (see Section 4.1 and Fig. 7 for detailed descriptions.)

Back to trap-beam problem: τ_n vs. β-asymmetry

Updated Fig.7 from Belfatto, Beradze and Z.B, EPJ C 80, 149 (2020)



$g_A = 1.27625(50)$

$\tau_{\rm beam} = 888.0 \pm 2.0$ s

$\tau_{\rm trap} = 878.5 \pm 0.5$ s

Free neutron decay:

$$G_V^2 = \frac{K/\ln 2}{\mathcal{F}_n \tau_n (1+3g_A^2)(1+\Delta_R)}$$

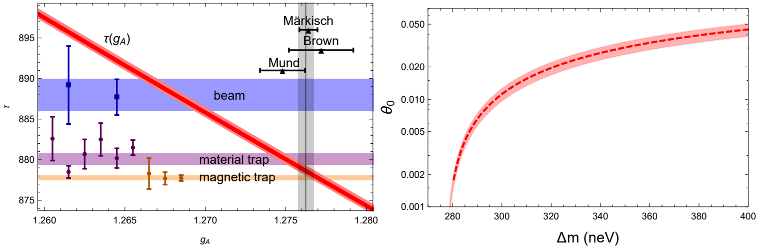
$0^+ - 0^+$ decays:

$$G_V^2 = \frac{K}{2\mathcal{F}t\,(1+\Delta_R)}$$

$$\tau_n = \frac{2\mathcal{F}t}{\mathcal{F}_n(1+3g_A^2)} = \frac{5172.1(1.1 \to 2.8)}{1+3g_A^2}\ \text{s}$$ Czarnecki et al. 2018

G_V and Δ_R cancel out even in BSM $G_V \neq G_F|V_{ud}|$: $g_A = -G_A/G_V$

$g_A = 1.27625(50) \longrightarrow \tau_n^{\rm theor} = 878.7 \pm (0.6 \to 1.5)$ s $\approx \tau_{\rm trap}$



$\tau_n^{\rm theor} = 878.7 \pm 1.5$ s $\qquad \tau_{\rm trap} = 878.5 \pm 0.5$ s (compatible)

$\tau_{\rm beam} = 888.0 \pm 2.0$ s $\quad (4.5\sigma)$

$\tau_{\rm mat} = 880.1 \pm 0.7$ s $\quad \tau_{\rm magn} = 877.8 \pm 0.3$ s $\quad$ (3.3σ discrepancy)

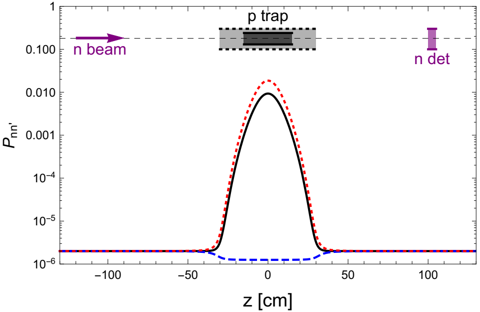
So experimentally we have $\quad \tau_{\rm magn} < \tau_{n\to p}^{\rm theor} < \tau_{\rm mat} < \tau_{\rm beam}$

which is possible in $n - n'$ oscillation scenario $\quad$ So far so Good!

Dark matter Factory ?

If my hypothesis is correct, a simple solenoid (magn. field ∼ Tesla) can be an effective machine transforming neutrons into DM neutrons

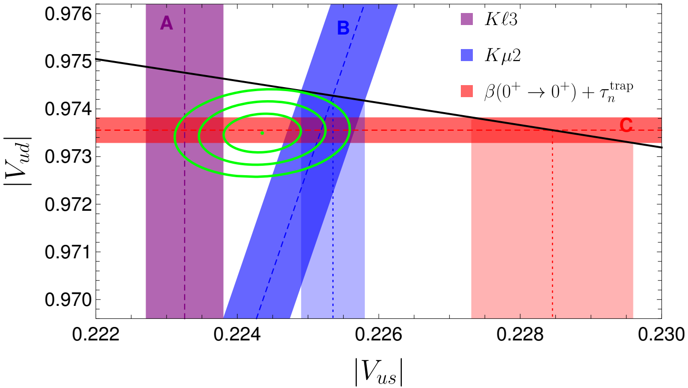
With good adiabatic conditions 50 % transformation can be achieved



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

ORNL experiment via $n \to n' \to n$ in strong magn. fields

Cabibbo Angle Anomaly



If CKM unitarity is assumed – strong discrepancy between

A: $|V_{us}| = \sin\theta_C$

B: $|V_{us}/V_{ud}| = \tan\theta_C$ Unitarity excluded at $> 3\sigma$

C: $|V_{ud}| = \cos\theta_C$