Unusual effects in $n - n'$ conversion

Sci-fi in two parts

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INT, Seattle, 22-27 Oct. 2017

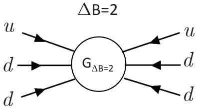
Contents

Preliminaries

Neutron – Antineutron Conversion

Neutron– antineutron oscillation

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



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

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

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

Present bounds on ϵ from nuclear stability

$\epsilon < 1.2 \times 10^{-24}$ eV	$\to$	$\tau > 1.3 \times 10^8$ s	Fe, Soudan 2002
$\epsilon < 2.5 \times 10^{-24}$ eV	$\to$	$\tau > 2.7 \times 10^8$ s	O, SK 2015

Free neutron– antineutron oscillation

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

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

Oscillation probability $P_{n\bar{n}}(t) = \frac{\epsilon^2}{\omega_B^2} \sin^2(\omega_B t)$, $\quad \omega_B = \mu_n B$

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

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

"Quasi-free" regime: for a given free flight time t, magnetic field should be properly suppressed to achieve $\omega_B t < 1$.
More suppression makes no sense !

Exp. Baldo-Ceolin et al, 1994 (ILL, Grenoble) : $t \simeq 0.1$ s, $\quad B < 100$ nT
$\tau > 2.7 \times 10^8 \quad \rightarrow \quad \epsilon < 7.7 \times 10^{-24}$ eV
At ESS 2 orders of magnitude better sensitivity can be achieved, down to $\epsilon \sim 10^{-25}$ eV

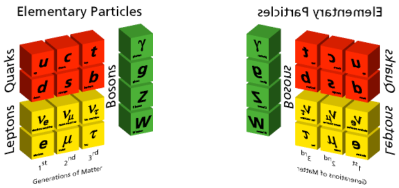
Chapter I

Getting Antimatter through Mirror Matter

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

$$G \times G'$$

Regular world | Mirror world



- Two identical gauge factors, e.g. $SU(5) \times SU(5)'$, with identical field contents and Lagrangians: $\mathcal{L}_{\rm tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\rm mix}$
- Exact parity $G \to G'$: no new parameters in dark Lagrangian $\mathcal{L}'$
- MM is dark (for us) and has the same gravity
- MM is identical to standard matter, (asymmetric/dissipative/atomic) but realized in somewhat different cosmological conditions: $T'/T \ll 1$.
- New interactions between O & M particles $\quad \mathcal{L}_{mix}$

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

Two parities

Fermions and anti-fermions :

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

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

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

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

Twin Fermions and anti-fermions :

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

B′=1/3 L′=1 B′=1/3 L′=1

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

B′=-1/3 L′=-1 B′=-1/3 L′=-1

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

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

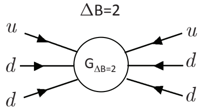
Mirror symmetry ($L, R \to R, L$ parity): $Y' = Y^*$ $\quad B - B' \to B - B'$

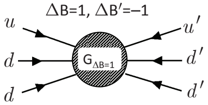
B violating operators between O and M particles

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)

$$\frac{1}{M^5}(udd)(udd) \text{ and } \frac{1}{M^5}(udd)(u'd'd') \quad (+ \text{h.c.})$$



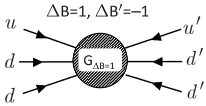


Oscillations $n(udd) \leftrightarrow \bar{n}(\bar{u}\bar{d}\bar{d})$ $(\Delta B = 2)$
$n(udd) \to \bar{n}'(\bar{u}'\bar{d}'\bar{d}')$, $n'(udd) \to \bar{n}(\bar{u}\bar{d}\bar{d})$ $(\Delta B = 1, \ \Delta B' = -1)$

Can co-generate Baryon asymmetries in both worlds
of the same sign, $B, B' > 0$, with $\Omega'_B \simeq 5\,\Omega_B$

Neutron – mirror neutron mixing

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



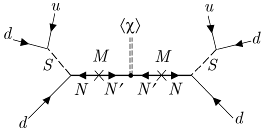
$$\beta = \langle n|(udd)(u'd'd')|\bar{n}'\rangle \sim \frac{\Lambda^6_{\mathrm{QCD}}}{M^5} \sim \left(\frac{10\ \mathrm{TeV}}{M}\right)^5 \times 10^{-15}\ \mathrm{eV}$$

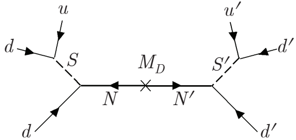
Key observation: *$n - \bar{n}'$ oscillation cannot destabilise nuclei:*
$(A, Z) \to (A-1, Z) + n'(p'e'\bar{\nu}')$ forbidden by energy conservation
(In principle, it can destabilise Neutron Stars)

$n - \bar{n}'$ oscillation can be as fast as $\beta^{-1} = \tau_{n\bar{n}'} \sim 1$ s, without contradicting experimental and astrophysical limits.
(c.f. $\tau_{n\bar{n}'} > 2.5 \times 10^8$ s for neutron – antineutron oscillation)

Neutron disappearance $n \to \bar{n}'$ and regeneration $n \to \bar{n}' \to n$ can be searched at small scale 'Table Top' experiments

Seesaw between ordinary and mirror neutrons





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

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

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

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

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

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

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

Neutron – mirror neutron oscillation probability

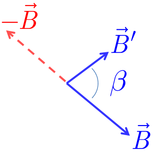
$$H = \begin{pmatrix} m_n + \mu_n \mathbf{B}\sigma & \alpha \\ \alpha & m_n + \mu_n \mathbf{B}'\sigma \end{pmatrix}$$

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

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

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

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



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

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

In Astrophysics

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

But neutrons bound in nuclei cannot oscillate into mirror twins.

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

But free neutrons are present only in

- Reactors and accelerators (challenge for $\tau_{n\bar{n}'} < 10^3$ s)
- In Cosmic Rays (fast $n' \to \bar{n}$ can solve UHECR puzzles)
- During BBN epoch (fast $n' \to \bar{n}$ can solve Lithium problem)

– Transition $n \to \bar{n}'$ can take place for (gravitationally) bound n in Neutron Stars – can be at the origin of pulsar glitches, conversion of NS into mixed ordinary/mirror NS, or NS evaporation (can be at the origin of heavy *trans-Iron* elements)

Getting Energy from Mirror World

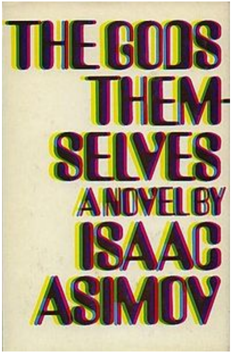
I argued (my previous talk) that in O and M worlds baryon asymmetries have same sign: $B, B' > 0$. So, mirror neutron n' oscillates into our antineutron, $n' \to \bar{n}$, and vice versa, $n \to \bar{n}'$

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

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

Positron Pump



First Part: Against Stupidity ...

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

Third Part: ... Contend in Vain?

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

Oscillation between four states

$n(udd)$, $\bar{n}(\bar{u}\bar{d}\bar{d})$; $n'(u'd'd')$, $\bar{n}'(\bar{u}'\bar{d}'\bar{d}')$

Oscillation between four states $(n, \bar{n}, n', \bar{n}')$, each with 2 spin states

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

Now $n \to \bar{n}$, $n \to n'$, $n \to \bar{n}'$ are possible

If $B' = 0$, in quasi-free regime $P_{n\bar{n}} = (\epsilon t)^2 + (\alpha\beta t^2)^2$
If $B' \gg 0$, in quasi-free regime $P_{n\bar{n}} = (\epsilon t)^2$
If $B' \gg 0$ and $B = B'$ (resonance) $P_{n\bar{n}} = (\alpha\beta t^2)^2$
with disappearance probability $P_{nn'} + P_{n\bar{n}'} = (\alpha t)^2 + (\beta t)^2$

$\epsilon < 10^{-24}$ eV $(\tau_{n\bar{n}} > 10^8 \text{ s})$, $\alpha, \beta < 10^{-15}$ eV $(\tau_{nn'} > 1 \text{ s})$

Shortcut to $n \to \bar{n}$ transition ? regeneration $n \to n' \to \bar{n}$
Interesting for Leah's HFIR experiment with scanning over B ?

Majorana Machine

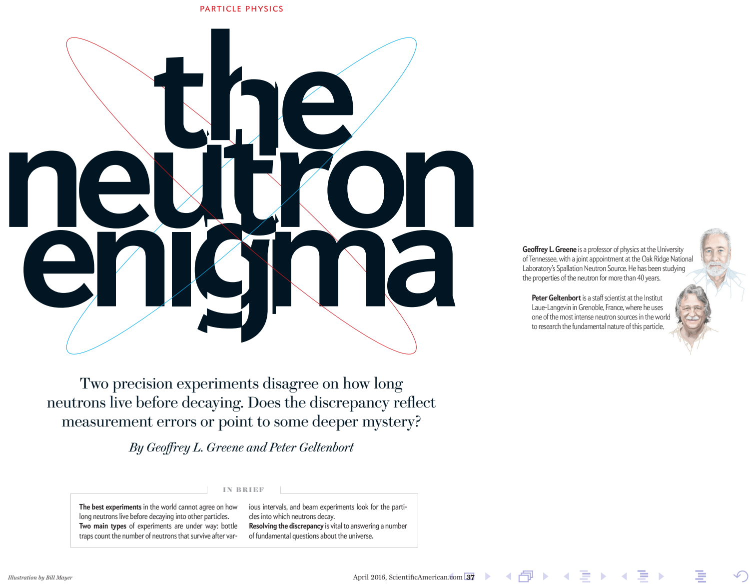
Can be neutrons efficiently transformed into antineutrons using Mirror World as shortcut ?

So we could get antimatter directly from matter

Chapter II

Not so Perfect Mirror ...

The neutron enigma ...



PARTICLE PHYSICS

the neutron enigma

Two precision experiments disagree on how long neutrons live before decaying. Does the discrepancy reflect measurement errors or point to some deeper mystery?

By Geoffrey L. Greene and Peter Geltenbort

Geoffrey L. Greene is a professor of physics at the University of Tennessee, with a joint appointment at the Oak Ridge National Laboratory's Spallation Neutron Source. He has been studying the properties of the neutron for more than 40 years.

Peter Geltenbort is a staff scientist at the Institut Laue-Langevin in Grenoble, France, where he uses one of the most intense neutron sources in the world to research the fundamental nature of this particle.

IN BRIEF

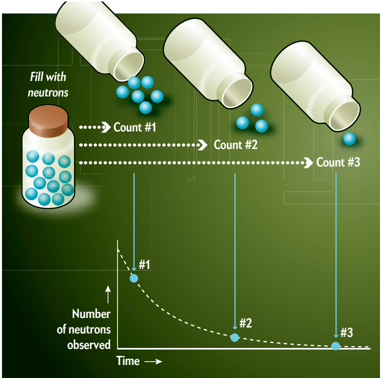
The best experiments in the world cannot agree on how long neutrons live before decaying into other particles.

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

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

Illustration by Bill Mayer

Two methods to measure the neutron lifetime

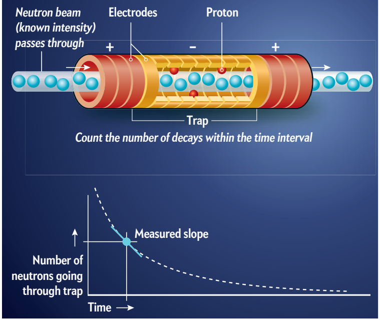


The Bottle Method

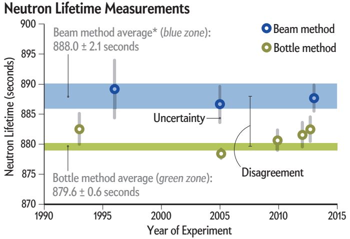
One way to measure how long neutrons live is to fill a container with neutrons and empty it after various time intervals under the same conditions to see how many remain. These tests fill in points along a curve that represents neutron decay over time. From this curve, scientists use a simple formula to calculate the average neutron lifetime. Because neutrons occasionally escape through the walls of the bottle, scientists vary the size of the bottle as well as the energy of the neutrons—both of which affect how many particles will escape from the bottle—to extrapolate to a hypothetical bottle that contains neutrons perfectly with no losses.

The Beam Method

In contrast to the bottle method, the beam technique looks not for neutrons but for one of their decay products, protons. Scientists direct a stream of neutrons through an electromagnetic "trap" made of a magnetic field and ring-shaped high-voltage electrodes. The neutral neutrons pass right through, but if one decays inside the trap, the resulting positively charged protons will get stuck. The researchers know how many neutrons were in the beam, and they know how long they spent passing through the trap, so by counting the protons in the trap they can measure the number of neutrons that decayed in that span of time. This measurement is the decay rate, which is the slope of the decay curve at a given point in time and which allows the scientists to calculate the average neutron lifetime.



Problems to meet ...



A few theorists have taken this notion seriously. Zurab Berezhiani of the University of L'Aquila in Italy and his colleagues have suggested such a secondary process: a free neutron, they propose, might sometimes transform into a hypothesized "mirror neutron" that no longer interacts with normal matter and would thus seem to disappear. Such mirror matter could contribute to the total amount of dark matter in the universe. Although this idea is quite stimulating, it remains highly speculative. More definitive confirmation of the divergence between the bottle and beam methods of measuring the neutron lifetime is necessary before most physicists would accept a concept as radical as mirror matter.

Why the neutron lifetime measured in UCN traps is smaller than that measured in beam method ? Missing decay channel seems impossible (neutron would be unstable also in nuclei).
But $n \to n'$ conversion can be plausible explanation
$+$ beta-decay of n' in invisible channel

Something new should be added – transitional magnetic moments between n and n′ (In preparation with Kamyshkov et al.)

$n - n'$ transitional magnetic moment

$n - n'$ mass mixing $\beta n C n' + \mathrm{h.c.}$

transitional magnetic moments $\mu_{nn'}(F_{\mu\nu} + F'_{\mu\nu}) n C \sigma^{\mu\nu} n' + \mathrm{h.c.}$

Hamiltonian of n and n' system becomes

$$H = \begin{pmatrix} m_n + \mu_n \mathbf{B}\sigma & \alpha + x\mu_n(\mathbf{B} + \mathbf{B}')\sigma \\ \alpha + x\mu_n(\mathbf{B} + \mathbf{B}')\sigma & m_n + \mu_n \mathbf{B}'\sigma \end{pmatrix}, \quad x = \frac{\mu_{nn'}}{\mu_n}$$

If $B \gg B'$ (or $B' \gg B$), oscillation probability becomes $P_{n\bar{n}'} = x^2$.

Interplay of α and $\mu_{nn'}$ can alleviate problem ....

Toccata: invisible decay

Imagine that mirror parity is not perfect,
but it is mildly broken (e.g. by some parity odd parity scalar)

So that particle masses in O and M sectors have tiny differences:

$m_n > m'_n$, $m_n - m'_n = \Delta m \leq 1$ MeV, and $|m'_p - m'_n| \simeq MeV$

Now free neutron can decay in invisible mode $n \to n' + \eta$, where η can be some massless boson. E.g. it can be Goldstone if mass mixing term $\beta n C n' + \mathrm{h.c.}$ emerges via spontaneous breaking of $U(1)_B \times U(1)'_B$ by some Higgs $\chi(1,1)$.

Trap method – the neutron total width: $\tau_{\rm dec}^{-1} = \Gamma_{\rm tot} = \Gamma_{\rm vis} + \Gamma_{\rm inv}$

beam method – beta-decay width $\Gamma_{\rm vis}(n \to pe\bar{\nu}) = \tau_{\rm inv}^{-1} \simeq 10^{-27}$ GeV.

$\Gamma_{\rm inv}(n \to n'\eta) \simeq 10^{-29}$ will suffice for 1 % discrepancy ...
E.g. if $m'_p > m_n > m_p > m'_n$, n' can be self-interacting DM ($\sigma/m \sim 1b/\mathrm{GeV}$), but also mirror hydrogen fraction can present and some mirror helium (as dissipative component)

... and Fuga: not so invisible decay via $\mu_{nn'}$

If decay occurs via transitional magnetic moment:

$$\Gamma(n \to n'\gamma', \gamma) = \frac{1}{8\pi}\mu_{nn'}^2 m_n^3 \left(1 - \frac{m_n'^2}{m_n^2}\right)^2 = 4\alpha^2 x^2 m_n (\Delta m/m_n)^3$$

Branching $\mathrm{Br}(n'\gamma) \simeq 10^{-2}$ can be obtained then for $\Delta m \simeq 1$ MeV and $x = \mu_{nn'}/\mu_n \sim 10^{-9}$

Imagine what incredible consequences for Neutron Star transformations ....

To be Continued ..... Stay Tuned !