Baryon number violation and neutron oscillations

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Sakharov's baryogenesis conditions

1. Baryon number violation ($\Delta B \neq 0$)
2. C and CP symmetry violation
3. Departure from thermal equilibrium

Sakharov (1967)

assuming "total CPT invariance of the (expanding) Universe"

Sakharov's baryogenesis conditions

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Sakharov (1967)

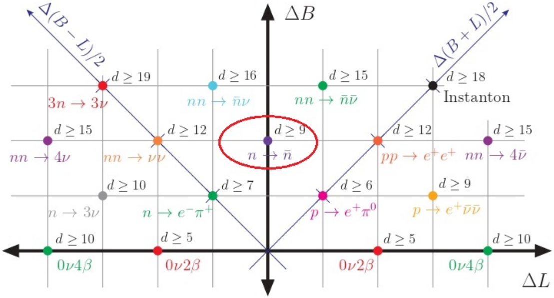
assuming "total CPT invariance of the (expanding) Universe"

Standard Model:

- B and L are automatically conserved in (renormalizable) couplings
- $B - L$ conserved also by non-perturbative effects

Beyond the Standard Model: $\Delta(B-L) \neq 0$

Landscape of baryon and lepton number violation



adapted from J. Heeck and V. Takhistov, PRD 101, 015005 (2020), 1910.07647 [hep-ph].

Some representative processes and the minimal mass dimension *d* of the underlying EFT operator

Neutron-antineutron oscillations

Baryon number violation and neutron oscillations

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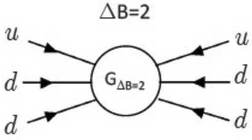


- Six-fermion effective operator $\frac{1}{M^5}(udd)(udd)$, $M > 1\,TeV$
- Effective renormalized $\Delta B = 2$ quadratic Lagrangian for Dirac field $n(x)$:

$$\mathcal{L} = \bar{n}(x) i\gamma^\mu \partial_\mu n(x) - m\bar{n}(x)n(x) - \epsilon[n^T(x)Cn(x) + \bar{n}(x)C\bar{n}^T(x)]$$

$$\epsilon = \langle n|(udd)(udd)|n\rangle \sim \frac{\Lambda_{QCD}^6}{M^5} = \frac{1}{\tau_{n\bar{n}}}$$

- $n\bar{n}$ oscillations distabilize the nuclei

$$(A, Z) \to (A-1, \bar{n}, Z) \to (A-2, Z/Z-1) + \text{pions}$$

Present experimental status:

- ILL (Grenoble): free neutron oscillations – the cleanest experimental and theoretical environment to perform the search

$$\tau_{n\bar{n}} > 2.7 \text{ years } (8.7 \times 10^7 \text{ s})$$

Baldo-Ceolin et al., ILL (1994)

  New experiment at ESS promises a sensitivity in oscillation probability up to three orders of magnitude greater than ILL (some proposals go up to 5 orders!).

- Super-Kamiokande: $n\bar{n}$ oscillation in ^{16}O

$$\tau_{n\bar{n}} > 8.6 \text{ years}$$

Abe et al., Super-Kamiokande collab. (2011)

- Sudbury Neutrino Observatory: $n\bar{n}$ oscillation in deuterium

$$\tau_{n\bar{n}} > 4.1 \text{ years}$$

Aharmim et al., SNO collab. (2017)

$N\bar{N}$ oscillations: short chronology

"CP-noninvariance and baryon asymmetry of the Universe"

Kuzmin (1970)

"Neutron Oscillations and the Existence of Massive Neutral Leptons"

Kuo and Love (1980)

"$B - L$ nonconservation and neutron oscillation"

Chang and Chang (1980)

"Phenomenology of neutron oscillation"

Marshak and Mohapatra (1980)

Some more recent models:

- Models with large (TeV scale) extra dimensions

Dvali, Gabadadze (2002)

Nussinov and Shrock (2002)

- Unified model $SU(2)_L \times SU(2)_R \times SU(4)_c$ with TeV scale seesaw

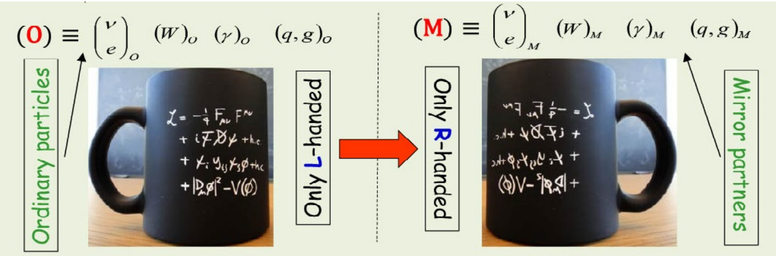
Babu, Dev and Mohapatra (2009)

- SO(10) GUT scale seesaw with TeV scalars

Babu and Mohapatra (2012)

Estimates of oscillation time: $\tau_{n\bar{n}} = 3 - 30\,000$ years

Beyond the Ordinary World: Mirror World



$$\left(SU(3)_c \times SU(2)_L \times U(1)_Y\right) \times \left(SU(3)'_c \times SU(2)'_L \times U(1)'_Y\right)$$

- Identical field contents (with opposite chirality) and Lagrangians
- Interactions between the O and M sectors by $\mathcal{L}_{mix}$ (portals)

$$\mathcal{L}_{tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{mix}$$

- Mirror worlds can be many...

Dvali, Savicki and Vikman (2009)

Mirror World as dark matter and LIGO unexpected events

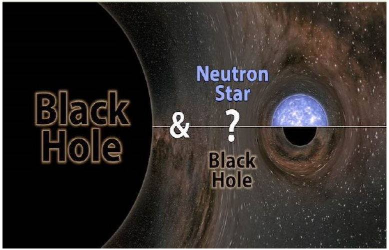
- Mirror world reheating temperature lower (constraints from Big Bang Nucleosynthesis): $T'/T < 0.64$
- Mirror world can explain all dark matter: $\Omega'_b/\Omega_b \approx 5$
- Stars are composed mainly of He, are more massive and evolve faster
- Number of stars: $N'(m) \sim 5 \times N(m)$
- Number of BH: $N'_{BH} \sim 10 \times N_{BH}$

for a review on mirror world, see Berezhiani (2005)

Mirror world could provide explanation for LIGO puzzles

Merger objects:	BH-BH	NS-NS	BH-NS	BH-Mass gap
Number of events:	84	2	2	2

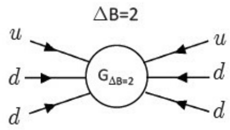
- Observed Merger Rates higher than theoretical predictions;
- Only one NS-NS observed event has electromagnetic counterpart
- Mass gap (BH or NS?) events observed

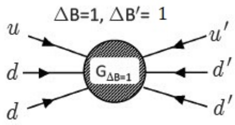


LIGO signals can come from the Mirror World!

Beradze and Gogberashvili (2019, 2021)

Neutron-mirror neutron oscillations





Berezhiani and Bento (2005)

$n - \bar{n}$ oscillations: $\Delta B = 2$

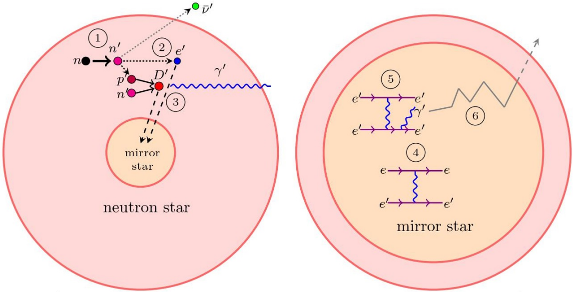
$n - \bar{n}'$, $n - n'$ oscillations: $\Delta B = 1$, $\Delta B' = 1$

- $\mathcal{L}_{mix}$: Dirac or Majorana-type mass terms
- The nn' oscillations can speed up in magnetic fields
- Current experimental limits: $\tau_{nn'}, \tau_{n\bar{n}'} > 50\ s$

Abel et al. (PSI) (2020)

Neutron-mirror neutron oscillations can cool the neutron stars

Goldman, Mohapatra, Nussinov and Zhang (2022)



(1) $n \to n'$ transition
(2) decay $n' \to p' + e' + \bar{\nu}'$ & $p' + n' \to D' + \gamma'$
(3) D' & e' falling into the center & forming mirror star
(4) energy transferring via $e + e' \to e + e'$
(5) γ' production via $e' + e' \to e' + e' + \gamma'$
(6) γ' emission from mirror star

$$\epsilon_{nn'} < 10^{-17} eV$$

$$\epsilon^2 \gg 10^{-27},$$

ϵ is a minute charge of e'

Neutron oscillations and CP violation: towards baryogenesis

- Most general effective Lagrangian with $\Delta B = 2$ for neutrons:

$$\begin{aligned}\mathcal{L} &= \bar{n}(x) i\gamma^\mu \partial_\mu n(x) - m\bar{n}(x)n(x) \\ &- \frac{i}{2}\epsilon_1 [e^{i\alpha}\bar{n}^T(x) C n(x) - e^{-i\alpha}\bar{n}(x) C \bar{n}^T(x)] \\ &- \frac{i}{2}\epsilon_5 [n^T(x) C\gamma_5 n(x) + \bar{n}(x)\gamma_5 C \bar{n}^T(x)],\end{aligned}$$

where n is Dirac field and *real* parameters m, ϵ_1, ϵ_5 and α

- The Lagrangian violates C, P, CP
- Claim: Neutron-antineutron oscillations violate CP: two of Sakharov's conditions are fulfilled!

Berezhiani and Vainshtein (2015)

- Observable CP violation $\equiv$ different transition probabilities:

$$P(neutron \to antineutron) \neq P(antineutron \to neutron)$$

- In spite of the intrinsic CP violation in the Lagrangian, the transition probabilities are the same:

$$P(neutron \to antineutron) = P(antineutron \to neutron)$$

- Transfer CP violating chiral $U(1)$ phase to parity violating mass term:

$$im'\bar{n}\gamma_5 n$$

- Intrinsic CP violation may be observed as contribution to EDM of neutron

Fujikawa and AT (2015, 2019)

- In chiral components,

$$-2\mathcal{L}_{mass} = \left(\overline{n_R} \quad n_L^T(x)C \right) \begin{pmatrix} M_R^\dagger & M_D \\ M_D & M_L \end{pmatrix} \begin{pmatrix} C\overline{n_R}^T \\ n_L \end{pmatrix} + h.c.$$

diagonalized using mixing matrix

$$U = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & e^{i\beta} \end{pmatrix}, \quad \beta - \text{Majorana phase}$$

Fujikawa and AT (2021)

- Consider simultaneously $n\bar{n}$ and nn', $n\bar{n}'$ oscillations
  - 4×4 mixing matrix
  - 3 Dirac phases, 3 Majorana phases

CP violation in neutron oscillations can be achieved

Kupiainen and AT (in preparation)