Neutron–Antineutron Oscillations: Theory Overview

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Outline

- Motivations for baryon number violation by 2 units
- $n - \bar{n}$ oscillations phenomenology
- Explicit models:
  - $SU(2)_L \times SU(2)_R \times SU(4)_C$ symmetry
  - SUSY with R-parity violation
  - Effective Field Theory framework
- Relating baryogenesis with $n - \bar{n}$ oscillations
- Neutron–sterile neutron oscillations
- Testing fundamental symmetries with $n - \bar{n}$
- Conclusions

Baryon Number Violation by 2 Units

- Baryon number is not believed to be a fundamental symmetry
- If $\Delta B = -1$, proton would decay $\Rightarrow$ Scale 10^{15} GeV
- If $\Delta B = -2$, n can oscillate into $\bar{n}$. Scale $\sim 10^5$ GeV
- Interesting theories predict $\Delta B = -2$, notably quark-lepton unified theories based on $SU(2)_L \times SU(2)_R \times SU(4)_C$

  Mohapatra-Marshak (1980)
- Supersymmetry with R parity violation via udd operators can lead to measurable $n - \bar{n}$ oscillations
- B violation with $\Delta B = -2$ can generate baryon asymmetry of the universe at low energy scale $n - \bar{n} \leftrightarrow B$ asymmetry
- Observation of $n - \bar{n}$ oscillations severely constrain fundamental symmetry violation: Lorentz symmetry, equivalence principle,..

Brief History of $n - \bar{n}$ theory

- Initially proposed by Kuzmin (1970): Motivated by suggestion of baryogenesis
- Glashow (1979) noted $n - \bar{n}$ oscillation in $SU(5)$ with a Higgs in 15-plet
- Marshak-Mohapatra (1980) developed theoretical ideas to testable level in left-right symmetric context
- Nuclear matrix element calculation undertaken: Shrock-Rao (1982)
- Connections of $n - \bar{n}$ with post-sphaleron baryogenesis observed: Mohapatra, Nasri, Babu (2006)
- $n - n'$ oscillation ideas developed: Bento-Berezhiani (2006)
- Tests of fundamental symmetries: Mohapatra, Babu (2015); Berezhiani-Kamyshkov (2016)
- Lattice calculations of $n - \bar{n}$ matrix element fully developed: Rinaldi et. al. (2018)

$n - \bar{n}$ oscillation Phenomenology

- n and $\bar{n}$ have opposite magnetic moments: $\mu_n = -1.9\mu_N$
- Oscillation in vacuum is inhibited by $\vec{\mu}.\vec{B}$ interactions with earth's magnetic field
- Time evolution of $n - \bar{n}$ system governed by:

$$\mathcal{M}_{\mathcal{B}} = \begin{pmatrix} m_n - \vec{\mu}_n \cdot \vec{B} - i\lambda/2 & \delta m \\ \delta m & m_n + \vec{\mu}_n \cdot \vec{B} - i\lambda/2 \end{pmatrix}$$

Here $1/\lambda = \tau_n = 880$ sec., m_n is neutron mass.

$$\mathcal{L} = m_n \, \bar{n} \, n + \frac{\delta m}{2} n^T \, C \, n$$

δm violates B by 2 units. ($\delta m = 0$ in standard model)

- Discovery of $n - \bar{n}$ oscillations would prove violation of baryon number

$n - \bar{n}$ oscillation Phenomenology (cont.)

- $n \to \bar{n}$ transition probability:

$$P(n \to \bar{n}) = \sin^2(2\theta)\sin^2(\Delta E t/2)e^{-\lambda t}$$
$$\Delta E \simeq 2|\vec{\mu_n}.\vec{B}|, \quad \tan(2\theta) = -\frac{\delta m}{\vec{\mu_n}.\vec{B}}$$

- Quasifree condition holds:

$$|\vec{\mu_n}.\vec{B}|t << 1$$

$$P(n \to \bar{n}) \simeq [(\delta m)t]^2 = [t/\tau_{n-\bar{n}}]^2$$

- Number of $\bar{n}$ created after time t is

$$N_{\bar{n}} = P(n \to \bar{n})N_n \simeq \phi T_{\rm run}[t/\tau_{n-\bar{n}}]^2$$

- Best limit on free neutron oscillation: $\tau_{n-\bar{n}} > 8.6 \times 10^7$ sec. Baldo-ceolin et. al., ILL (1994)

$n - \bar{n}$ oscillation Phenomenology (cont.)

- $n - \bar{n}$ transition can occur in nuclei. However, energy difference is of order 30 MeV, suppressing oscillation by a large factor:

$$\tau_{Nuc} = R\tau_{n\bar{n}}^2, \quad R \simeq 5 \times 10^{22}\,\mathrm{sec}^{-1}$$

  Chetyrkin et. al (1981); Dover, Gal, Richards (1995); Kopeliovich et. al. (2012),...

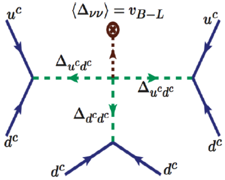
- Best limit from SuperK: $\tau_{n\bar{n}} > 3.5 \times 10^8$ sec.
- $\Rightarrow \delta m < 10^{-23}$ eV
- For free neutron oscillations degaussing of earth's magnetic field to level nano-Tesla required for improved determination

Models of $n - \bar{n}$ oscillations

- Effective $\Delta B = 2$ operator that mediates neutron oscillation is:

$$\mathcal{L}_{\rm eff} = \frac{(udd)^2}{\Lambda^5}$$

- High dimension implies oscillations probe scale of $\Lambda \sim 10^6$ GeV
- This operator naturally arises in quark-lepton unified theories based on $SU(2)_L \times SU(2)_R \times SU(4)_C$ as partners of seesaw mechanism for neutrinos.
- Δ fields are color sextet scalars, which do not mediate proton decay. $\mathcal{L}_{\rm eff} = (\lambda f^3 v_{BL})/M^6$



From quarks to nucleons

- The quark level Lagrangian needs to be converted to nucleon level δm
- MIT bag model calculations showed $\delta m \simeq \Lambda_{QCD}^6/\Lambda^5$ with $\Lambda_{QCD} \simeq 200$ MeV Shrock-Rao (1982)
- Recent lattice calculations show enhancement of oscillation probability by an order of magnitude Rinaldi et. al. (2018)
- For $n - \bar{n}$ transition in nuclei, nuclear physics calculations have been improving Friedman, Gal (2008)

Effective $n - \bar{n}$ operators

- There are 12 quark level operators:

$$\mathcal{L}_{\rm eff} \supset \sum_{i=1}^{6} c_i \mathcal{O}_i + \bar{c}_i \bar{\mathcal{O}}_i + \text{h.c.}$$

- These operators have the form (Wagman-Buchoff basis):

$$\begin{aligned}
\mathcal{O}_1 &= \frac{1}{2}\epsilon_{ijk}\epsilon_{i'j'k'}(\bar{u}_i^c P_R d_j)(\bar{u}_{i'}^c P_R d_{j'})(\bar{d}_k^c P_R d_{k'}) \,, \\
\mathcal{O}_2 &= \epsilon_{ijk}\epsilon_{i'j'k'}(\bar{u}_i^c P_L d_j)(\bar{u}_{i'}^c P_R d_{j'})(\bar{d}_k^c P_R d_{k'}) \,, \\
\mathcal{O}_3 &= \frac{1}{2}\epsilon_{ijk}\epsilon_{i'j'k'}(\bar{u}_i^c P_L d_j)(\bar{u}_{i'}^c P_L d_{j'})(\bar{d}_k^c P_R d_{k'}) \,, \\
\mathcal{O}_4 &= \epsilon_{ijk}\epsilon_{i'j'k'}(\bar{u}_i^c P_R u_{i'})(\bar{d}_j^c P_L d_{j'})(\bar{d}_k^c P_L d_{k'}) \,, \\
\mathcal{O}_5 &= \left(\epsilon_{ijk}\epsilon_{i'j'k'} + \epsilon_{i'jk}\epsilon_{ij'k'}\right)(\bar{u}_i^c P_R d_{i'})(\bar{u}_j^c P_L d_{j'})(\bar{d}_k^c P_L d_{k'}) \,, \\
\mathcal{O}_6 &= \epsilon_{ijk}\epsilon_{i'j'k'}(\bar{u}_i^c P_L u_{i'})(\bar{d}_j^c P_L d_{j'})(\bar{d}_k^c P_R d_{k'}) \\
&\quad + \left(\epsilon_{ijk}\epsilon_{i'j'k'} + \epsilon_{i'jk}\epsilon_{ij'k'}\right)(\bar{u}_i^c P_L d_{i'})(\bar{u}_j^c P_L d_{j'})(\bar{d}_k^c P_R d_{k'})
\end{aligned}$$

Baryon Asymmetry from $n - \bar{n}$ oscillations

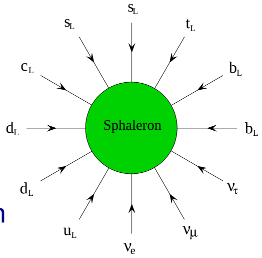
- Observed baryon asymmetry:
$$Y_{\Delta B} = \frac{n_B - n_{\overline{B}}}{s} = (8.75 \pm 0.23) \times 10^{-11}$$
- Sakharov conditions must be met to dynamically generate $Y_{\Delta B}$
  - Baryon number (B) violation
  - C and CP violation
  - Departure from thermal equilibrium
- All ingredients are present in Grand Unified Theories. However, in simple GUTs such as $SU(5)$, $B - L$ is unbroken
- Electroweak sphalerons, which are in thermal equilibrium from $T = (10^2 - 10^{12})$ GeV, wash out any $B - L$ preserving asymmetry generated at any $T > 100$ GeV

Kuzmin, Rubakov, Shaposhnikov (1985)

Baryon Asymmetry from $n - \bar{n}$ oscillations

- Sphaleron: Non-perturbative configuration of the electroweak theory
- Leads to effective interactions of left-handed fermions:

$$O_{B+L} = \prod_i (q_i q_i q_i L_i)$$



- Obeys $\Delta B = \Delta L = 3$
- Sphaleron can convert lepton asymmetry to baryon asymmetry – Leptogenesis mechanism (Fukugita, Yanagida (1986))
- Post-sphaleron baryogenesis: Baryon number is generated below 100 GeV, after sphalerons go out of equilibrium (Babu, Nasri, Mohapatra (2006))

Post-Sphaleron Baryogenesis

- A scalar (S) or a pseudoscalar (η) decays to baryons, violating B
- $\Delta B = 1$ is strongly constrained by proton decay and cannot lead to successful post-sphaleron baryogenesis
- $\Delta B = 2$ decay of S/η can generate baryon asymmetry below $T = 100$ GeV: $S/\eta \to 6\,q; \quad S/\eta \to 6\,\overline{q}$
- Decay violates CP, and occurs out of equilibrium
- Naturally realized in quark-lepton unified models, with S/η identified as the Higgs boson of $B - L$ breaking
- $\Delta B = 2 \Rightarrow$ connection with $n - \overline{n}$ oscillation
- Quantitative relationship exists in quark-lepton unified models based on $SU(2)_L \times SU(2)_R \times SU(4)_C$

Quark-Lepton Symmetric Models

- Quark-lepton symmetric models based on the gauge group $SU(2)_L \times SU(2)_R \times SU(4)_C$ have the necessary ingredients for PSB Pati-Salam (1973)
- There is no $\Delta B = 1$ processes since $B - L$ is broken by 2 units. Thus there is no rapid proton decay. Symmetry may be realized in the 100 TeV range
- There is baryon number violation mediated by scalars, which are the partners of Higgs that lead to seesaw mechanism Mohapatra, Marshak (1980)
- Scalar fields S/η arise naturally as Higgs bosons of $B - L$ breaking
- Yukawa coupling that affect PSB and $n - \overline{n}$ oscillations are the same as the ones that generate neutrino masses

Quark-Lepton Symmetric Models

- Models based on $SU(2)_L \times SU(2)_R \times SU(4)_C$ (Pati-Salam)
- Fermions, including ν_R, belong to $(2,1,4) \oplus (1,2,4)$
- Symmetry breaking and neutrino mass generation needs Higgs field $\Delta(1,3,\overline{10})$. Under $SU(2)_L \times U(1)_Y \times SU(3)_C$:

$$\begin{aligned}\Delta(1,3,\overline{10}) \quad = \quad & \Delta_{uu}(1,-\frac{8}{3},6^*) \oplus \Delta_{ud}(1,-\frac{2}{3},6^*) \oplus \Delta_{dd}(1,+\frac{4}{3},6^*) \oplus \Delta_{ue}(1,\frac{2}{3},3^*) \\ & \oplus \Delta_{u\nu}(1,-\frac{4}{3},3^*) \oplus \Delta_{de}(1,\frac{8}{3},3^*) \oplus \Delta_{d\nu}(1,\frac{2}{3},3^*) \oplus \Delta_{ee}(1,4,1) \\ & \oplus \Delta_{\nu e}(1,2,1) \oplus \Delta_{\nu\nu}(1,0,1) \; .\end{aligned}$$

- Δ_{uu}, Δ_{ud}, Δ_{dd} are diquarks, Δ_{ue}, $\Delta_{u\nu}$, Δ_{de}, $\Delta_{d\nu}$ are leptoquarks, and $\Delta_{\nu\nu}$ is a singlet that breaks the symmetry
- Diquarks generate B violation, leptoquarks help with CP violation, and singlet $\Delta_{\nu\nu}$ provides the field S/η for PSB

Quark-Lepton Symmetric Models (cont.)

- Interactions of color sextet diquarks and B violating couplings:

$$\mathcal{L}_I = \frac{f_{ij}}{2}\Delta_{dd} d_i d_j + \frac{h_{ij}}{2}\Delta_{uu} u_i u_j + \frac{g_{ij}}{2\sqrt{2}}\Delta_{ud}(u_i d_j + u_j d_i) + \frac{\lambda}{2}\Delta_{\nu\nu}\Delta_{dd}\Delta_{ud}\Delta_{ud} + \lambda'\Delta_{\nu\nu}\Delta_{uu}\Delta_{dd}\Delta_{dd} + \mathrm{h.c.}$$

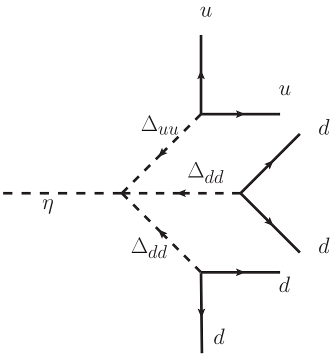
- $f_{ij} = g_{ij} = h_{ij}$ and $\lambda = \lambda'$ from gauge symmetry.
- We also introduce a scalar $\chi(1,2,4)$ which couples to $\Delta(1,3,\overline{10})$ via $(\mu\chi\chi\Delta \supset \chi_\nu\chi_\nu\Delta_{\nu\nu} + \ldots)$
- Among the phases of $\Delta_{\nu\nu}$ and χ_ν, one combination is eaten by $B-L$ gauge boson. The other, is a pseudoscalar η:

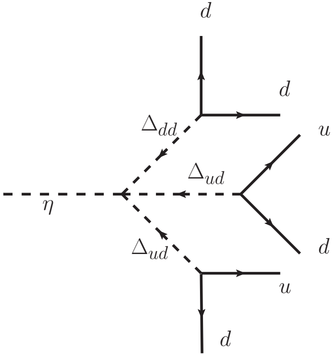
$$\Delta_{\nu\nu} = \frac{(\rho_1 + v_R)}{\sqrt{2}} e^{i\eta_1/v_R}, \chi_\nu = \frac{(\rho_2 + v_B)}{\sqrt{2}} e^{i\eta_2/v_B}, \eta = \frac{2\eta_2 v_R - \eta_1 v_B}{\sqrt{4v_R^2 + v_B^2}}$$

- Advantage of using $\eta \to 6\,q$ is that η has a flat potential due to a shift symmetry

Baryon violating decay of η

$\eta \to 6q$ and $\eta \to 6\overline{q}$ decays violate B:





Baryon violating decay of η (cont.)

- B-violating decay rate of η:

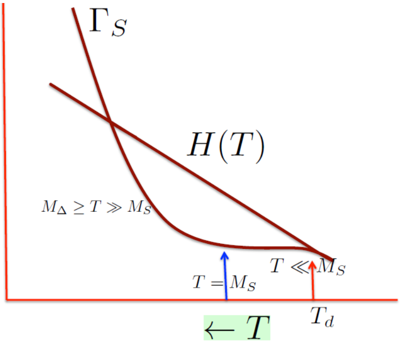
$$\Gamma_\eta \equiv \Gamma(\eta \to 6q) + \Gamma(\eta \to 6\bar{q}) = \frac{P}{\pi^9 \cdot 2^{25} \cdot 45} \frac{12}{4} |\lambda|^2 \mathrm{Tr}(f^\dagger f)[\mathrm{Tr}(\hat{g}^\dagger \hat{g})]^2 \left(\frac{M_\eta^{13}}{M_{\Delta_{ud}}^8 M_{\Delta_{dd}}^4} \right)$$

- Here P is a phase space factor:

$$P = \begin{cases} 1.13 \times 10^{-4} & (M_{\Delta_{ud}}/M_S, M_{\Delta_{dd}}/M_S \gg 1) \\ 1.29 \times 10^{-4} & (M_{\Delta_{ud}}/M_S = M_{\Delta_{dd}}/M_S = 2) \ . \end{cases}$$

- T_d is obtained by setting this rate to Hubble rate. For $T_d = (100$ MeV -100 GeV), $f \sim g \sim h \sim 1$, $M_{\Delta_{ud}} \sim M_\eta$ needed
- η has a competing $B = 0$ four-body decay mode, which is necessary to generate CP asymmetry: $\eta \to (uu)\Delta_{u\nu}\Delta_{u\nu}$
- The six-body and four-body decays should have comparable widths, or else B asymmetry will be too small

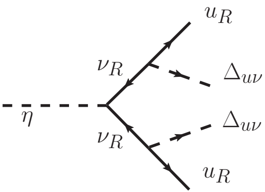
Thermal history of scalar decay



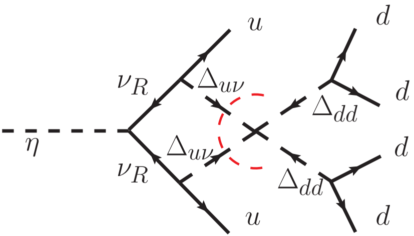
At $T = T_d$, scalar starts decaying: $200\ \mathrm{MeV} < T_d < 100$ GeV

Baryon conserving decay of η

$\eta \to (uu)\Delta_{u\nu}\Delta_{u\nu}$



This generates absorptive part and CP violation in $\eta \to 6q$:



Baryon Asymmetry

- $\eta \to uu\Delta_{u\nu}\Delta_{u\nu}$ has a width:

$$\Gamma_\eta \equiv \Gamma(\eta \to uu\Delta_{u\nu}\Delta_{u\nu}) + \Gamma(\eta \to \overline{uu}\Delta - u\nu^* \Delta^*_{u\nu}) = \frac{P}{1024\pi^5}[\mathrm{Tr}(\hat{f}^\dagger \hat{f})]^3 \left(\frac{M_\eta^5}{M_{\nu_R}^4}\right)$$

- Here P is a phase space factor, $P \simeq 2 \times 10^{-3}$
- For $\lambda = 1$, $\Gamma_6 \simeq (7 \times 10^{-9}) \times \Gamma_4 \times \frac{M_{\nu_R}^4}{M_{\Delta_{dd}}^4}$
- Baryon asymmetry:

$$\epsilon_B \simeq \frac{|f|^2 \mathrm{Im}(\lambda\tilde{\lambda})}{8\pi(|\lambda|^2 + \Gamma_4/\Gamma_6)} \left(\frac{M_{\Delta_{dd}}^2}{M_{\nu_R}^2}\right)$$

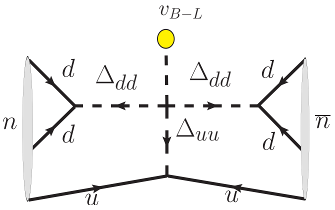
- With $M_{\nu_R} \sim 100 \times M_{\Delta_{dd}}$, $\Gamma_4 \sim \Gamma_6$. This choice maximizes ϵ_B:

$$\epsilon_B \sim (8 \times 10^{-5}) \times \frac{|f|^2}{8\pi} \mathrm{Im}(\frac{\tilde{\lambda}}{\lambda})$$

- For $f \sim \lambda \sim 1$, reasonable baryon asymmetry is generated with a dilution $d \sim 10^{-3}$

Connection with $n - \overline{n}$ oscillation

As η is associated with $B - L$ symmetry breaking, replacing η by the vacuum expectation value, $n - \overline{n}$ oscillation results:



$M_\eta \sim 3\,TeV$, $M_{\Delta_{ud}} \sim 4\,TeV$, $M_{\Delta_{dd}} \sim 50\,TeV$, $M_{\Delta u\nu} \sim 1\,TeV$, $v_{B-L} \sim 300\,TeV$ is a consistent choice

Flavor dependence of baryon asymmetry can be fixed via neutrino mass generation

Prediction for $n - \bar{n}$ oscillation

In a specific quark-lepton symmetric model Dev, Fortes, Mohapatra, Babu (2013)

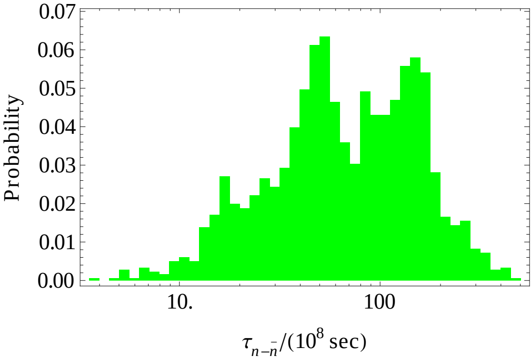
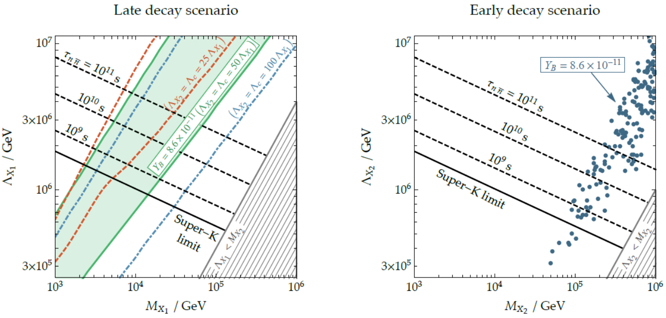


Figure: The likelihood probability for a particular value of $\tau_{n-\bar{n}}$ as given by the model parameters.

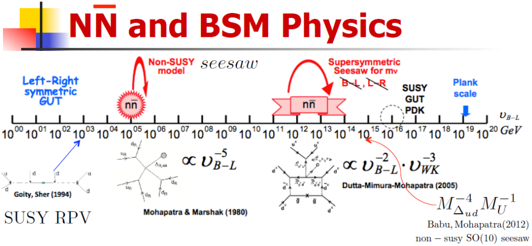
EFT for $n - \bar{n}$ oscillations and baryogenesis

- Recently Grojean, Shakya, Wells, Zhang (2018) have proposed a minimal EFT for baryogenesis
- They assume two couplings: $uddX_1$ and $uddX_2$ where X_i are singlet Majorana fermions
- This is sufficient to induce baryon asymmetry.



Other models of $n - \bar{n}$ oscillations

- Supersymmetry with R-parity violation Goity, Sher (1995); Mohapatra, Babu (2001); Csaki, Grossman, Heidenreinch (2012),...
- GUT with TeV-scale colored scalars Mohapatra, Babu (2012); Aswathi, Parida, Sahu (2014),...
- Flavor geography with TeV scale B violation Nussinov, Shrock (2002); Winslow, Ng (2010); Dvali, Gabadadze
- TeV scale B violating theories (Arnold, Fornal, Perez, Wise, Gu, Sarkar,...)



(Fig. Courtesy of Yuri Kamyshkov)

$n - n'$ oscillation

- There may exist a shadow universe with replica of all particles, including a mirror neutron n' Bento, Berezhiani (2006)
- The n and n' are nearly mass degenerate, $n - n'$ oscillations can occur. This is a $\Delta B = -1$ process
- Neutron can disappear, and may reappear at a distance
- Experimental limits on such oscillations are weak: $\tau_{n-n;} > 448$ sec. Serebrov et. al. (2009)
- Uncertainty with mirror magnetic field Berezhiani et. al. (2018)
- Improved measurements are ongoing L. Broussard et. al. (2019); Abel et. al (2019)

See Leah Broussard's talk today

Shortcut to $n - \bar{n}$ oscillations via n'

- Recently Berezhiani has suggested a shortcut to $n - \bar{n}$ oscillations via intermediate n' states.
- $n - n'$ as well as $n - \bar{n}'$ transitions are crucial for this setup

$$P(n - \bar{n})(t) = P(n - n')(t) P(n - \bar{n}')(t) \simeq \left(\frac{t}{0.1\,\mathrm{sec.}}\right)^4 \times 10^{-8}$$

- This is a much higher probability for conventional oscillations:

$$P(n - \bar{n}) \simeq (t/0.1\ \mathrm{sec})^2 \times 10^{-18}$$

- $(n,\ \bar{n},\ n',\ \bar{n}')$ Hamiltonian:

$$H = \begin{pmatrix} U_n + \boldsymbol{\Omega\sigma} & 0 & \epsilon & \kappa \\ 0 & U_{\tilde{n}} - \boldsymbol{\Omega\sigma} & \kappa & \epsilon \\ \epsilon & \kappa & U_{n'} + \boldsymbol{\Omega'\sigma} & 0 \\ \kappa & \epsilon & 0 & U_{\tilde{n}'} - \boldsymbol{\Omega'\sigma} \end{pmatrix}$$

Fundamental symmetries and $n - \bar{n}$ oscillations

- Observation of free neutron oscillations can provide stringent tests of Lorentz invariance, equivalence principle violation, long-range baryonic forces, etc.
- Existence of such violations would suppress $n - \bar{n}$ oscillations of free neutrons
- Transition in matter would be masked by nuclear potential difference
- Examples of derivable limits:
  - Lorentz violating mass term: 10^{-23} GeV
  - Equivalence principle: $\alpha_n - \alpha_{\bar{n}} < 10^{-18}$ Mohapatra, Babu (2018)
  - Long range baryonic force: $\alpha_B < 10^{-57}$ Addazi, Berezhiani, Kamyshkov (2016); Mohapatra, Babu (2016)

Illustration: Lorentz Violation

- Lorentz invariance violation parametrized as:
$$\mathcal{L}_{LIV} = a_\mu \overline{n}\gamma^\mu n - i c_{\mu\nu}\overline{n}\gamma^\mu \partial^\nu n + h.c.$$
- When $\langle a^0 \rangle \neq 0$ and $\langle c_{00} \rangle \neq 0$ Lorentz violating couplings are induced:
$$\mathcal{L}_{LIV} = \delta^{(1)}_{LV} n^\dagger n - i\delta^{(2)}_{LV} n^\dagger \partial^0 n + h.c.$$
- $\delta^{(1)}_{LV}$ inhibits free neutron oscillations, and could be bounded by
$$\delta^{(1)}_{LV} < 10^{-23}\ \text{GeV}$$
- $n - \bar{n}$ mixing Hamiltonian, after spin decomposition becomes (Gardner)

$$M_{4\times 4} = \begin{pmatrix} m + \delta^{(1)}_{LV} + m\delta^{(2)}_{LV} & \delta_{B=2} & 0 & 0 \\ \delta_{B=2} & m - \delta^{(1)}_{LV} + m\delta^{(2)}_{LV} & 0 & 0 \\ 0 & 0 & m + \delta^{(1)}_{LV} + m\delta^{(2)}_{LV} & -\delta_{B=2} \\ 0 & 0 & -\delta_{B=2} & m - \delta^{(1)}_{LV} + m\delta^{(2)}_{LV} \end{pmatrix}.$$

Constraining long-range baryonic forces

- α_B : strength of Yukawa potential; R_0 = Radius of Earth
  R: Range of new force

$$\frac{\delta m}{M_n} = \frac{2\alpha_B N_B^{\rm Earth}}{m_N R_0} = 1.2 \times 10^{29}\alpha_B$$

Adazzi, Berezhiani, Kamyshkov (2016); Mohapatra, Babu(2016)

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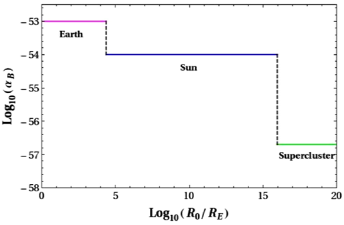

Conclusions

- Neutron-antineutron oscillations have very high potential to probe fundamental physics to a high scale
- It can also test fundamental symmetry principles at unprecedented levels
- Good reasons to suspect that these $\Delta B = 2$ interactions may be the source of baryon asymmetry of the universe