Neutron–Antineutron Oscillations: Theory Overview

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BNV Circa 2020
July 6 – 8, 2020
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 $10^{15} \text{ GeV}$
- If $\Delta B = -2$, $n$ can oscillate into $\bar{n}$. Scale $\sim 10^5 \text{ GeV}$
- 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
- 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:

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

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

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

$\delta m$ violates $B$ by 2 units. ($\delta m = 0$ in standard model)
- Discovery of $n - \bar{n}$ oscillations would prove violation of baryon number
$n \rightarrow \bar{n}$ oscillation Phenomenology (cont.)

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

$$P(n \rightarrow \bar{n}) = \sin^2(2\theta) \sin^2(\Delta E t/2) e^{-\lambda t}$$

$$\Delta E \simeq 2|\vec{\mu}_n \cdot \vec{B}|, \quad \tan(2\theta) = -\frac{\delta m}{\vec{\mu}_n \cdot \vec{B}}$$

- Quasifree condition holds:

$$|\vec{\mu}_n \cdot \vec{B}| t << 1$$

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

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

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

- 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:

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

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

- Best limit from SuperK: $\tau_{n\bar{n}} > 3.5 \times 10^8 \text{ sec.}$

$\Rightarrow \delta m < 10^{-23} \text{ eV}$

- 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:
  \[
  \mathcal{L}_{\text{eff}} = \frac{(udd)^2}{\Lambda^5}
  \]

- 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.

- $\Delta$ fields are color sextet scalars, which do not mediate proton decay. $\mathcal{L}_{\text{eff}} = (\lambda f^3 v_{BL})/M^6$
From quarks to nucleons

- The quark level Lagrangian needs to be converted to nucleon level $\delta m$.

- MIT bag model calculations showed $\delta m \approx \frac{\Lambda_{QCD}^6}{\Lambda_{QCD}^5}$ with $\Lambda_{QCD} \approx 200$ 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:

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

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

$$O_1 = \frac{1}{2} \varepsilon_{ijk} \varepsilon_{i' j' k'} (\bar{u}_i^c P_R d_j)(\bar{u}_{i'}^c P_R d_{j'}) (\bar{d}_k^c P_R d_{k'}) ,$$

$$O_2 = \varepsilon_{ijk} \varepsilon_{i' j' k'} (\bar{u}_i^c P_L d_j)(\bar{u}_{i'}^c P_R d_{j'}) (\bar{d}_k^c P_R d_{k'}) ,$$

$$O_3 = \frac{1}{2} \varepsilon_{ijk} \varepsilon_{i' j' k'} (\bar{u}_i^c P_L d_j)(\bar{u}_{i'}^c P_L d_{j'}) (\bar{d}_k^c P_R d_{k'}) ,$$

$$O_4 = \varepsilon_{ijk} \varepsilon_{i' j' k'} (\bar{u}_i^c P_R u_{i'})(\bar{d}_j^c P_L d_{j'}) (\bar{d}_k^c P_L d_{k'}) ,$$

$$O_5 = (\varepsilon_{ijk} \varepsilon_{i' j' k'} + \varepsilon_{i' jk} \varepsilon_{ij' k'}) (\bar{u}_i^c P_R d_{i'})(\bar{u}_{j'}^c P_L d_{j'}) (\bar{d}_k^c P_L d_{k'}) ,$$

$$O_6 = \varepsilon_{ijk} \varepsilon_{i' j' k'} (\bar{u}_i^c P_L u_{i'}) (\bar{d}_j^c P_L d_{j'})(\bar{d}_k^c P_R d_{k'})$$

$$+ (\varepsilon_{ijk} \varepsilon_{i' j' k'} + \varepsilon_{i' jk} \varepsilon_{ij' k'}) (\bar{u}_i^c P_L d_{i'})(\bar{u}_{j'}^c P_L d_{j'}) (\bar{d}_k^c P_R d_{k'})$$
Baryon Asymmetry from $n - \bar{n}$ oscillations

- Observed baryon asymmetry:
  \[ Y_{\Delta B} = \frac{n_B - n_{\bar{B}}}{s} = (8.75 \pm 0.23) \times 10^{-11} \]

- 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 \(\eta\) 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 \(S/\eta\) can generate baryon asymmetry below \(T = 100\) GeV: \(S/\eta \rightarrow 6q;\) \(S/\eta \rightarrow 6\bar{q}\)
- Decay violates CP, and occurs out of equilibrium
- Naturally realized in quark-lepton unified models, with \(S/\eta\) identified as the Higgs boson of \(B - L\) breaking
- \(\Delta B = 2\) \(\Rightarrow\) connection with \(n - \bar{n}\) 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 $S/\eta$ arise naturally as Higgs bosons of $B - L$ breaking.

- Yukawa coupling that affect PSB and $n - \bar{n}$ 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 $\nu_R$, belong to $(2, 1, 4) \oplus (1, 2, 4)$
- Symmetry breaking and neutrino mass generation needs Higgs field $\Delta(1, 3, \overline{10})$. Under $SU(2)_L \times U(1)_Y \times SU(3)_C$:

  $$\Delta(1, 3, \overline{10}) = \Delta_{uu}(1, -\frac{8}{3}, 6^*) \oplus \Delta_{ud}(1, -\frac{2}{3}, 6^*) \oplus \Delta_{dd}(1, +\frac{4}{3}, 6^*) \oplus \Delta_{ue}(1, \frac{2}{3}, 3^*)$$

  $$\oplus \Delta_{u\nu}(1, -\frac{4}{3}, 3^*) \oplus \Delta_{de}(1, \frac{8}{3}, 3^*) \oplus \Delta_{d\nu}(1, \frac{2}{3}, 3^*) \oplus \Delta_{ee}(1, 4, 1)$$

  $$\oplus \Delta_{\nu e}(1, 2, 1) \oplus \Delta_{\nu\nu}(1, 0, 1).$$

- $\Delta_{uu}$, $\Delta_{ud}$, $\Delta_{dd}$ are diquarks, $\Delta_{ue}$, $\Delta_{u\nu}$, $\Delta_{de}$, $\Delta_{d\nu}$ 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 $S/\eta$ for PSB
Interactions of color sextet diquarks and $B$ violating couplings:

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

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

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

- Advantage of using $\eta \rightarrow 6q$ is that $\eta$ has a flat potential due to a shift symmetry.
Baryon violating decay of $\eta$

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

\begin{figure}
\centering
\includegraphics[width=\textwidth]{diagram.png}
\end{figure}
Baryon violating decay of $\eta$ (cont.)

- **$B$-violating decay rate of $\eta$:**

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

- 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 $T_d = (100 \text{ MeV} - 100 \text{ GeV})$, $f \sim g \sim h \sim 1$, $M_{\Delta_{ud}} \sim M_{\eta}$ needed

- $\eta$ has a competing $B = 0$ four-body decay mode, which is necessary to generate CP asymmetry: $\eta \to (uu)\Delta_{uv}\Delta_{uv}$

- 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: $200 \text{ MeV} < T_d < 100 \text{ GeV}$
Baryon conserving decay of $\eta$

$$\eta \rightarrow (uu)\Delta_{uv}\Delta_{uv}$$

This generates absorptive part and CP violation in $\eta \rightarrow 6q$: 
Baryon Asymmetry

- $\eta \rightarrow uu\Delta_{u\nu}\Delta_{u\nu}$ has a width:
  $$\Gamma_\eta \equiv \Gamma(\eta \rightarrow uu\Delta_{u\nu}\Delta_{u\nu}) + \Gamma(\eta \rightarrow \bar{u}\bar{u}\Delta - u\nu^*\Delta_{u\nu}^*) = \frac{P}{1024\pi^5} [\text{Tr}(\hat{f}^\dagger \hat{f})]^3 \left( \frac{M_\eta^5}{M_{\nu_R}^4} \right)$$

- Here $P$ is a phase space factor, $P \approx 2 \times 10^{-3}$

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

- With $M_{\nu_R} \sim 100 \times M_{\Delta_{dd}}$, $\Gamma_4 \sim \Gamma_6$. This choice maximizes $\epsilon_B$:
  $$\epsilon_B \sim (8 \times 10^{-5}) \times \frac{|f|^2 \text{Im}(\frac{\tilde{\lambda}}{\lambda})}{8\pi}$$

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

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

\[ M_\eta \sim 3\,\text{TeV}, \quad M_{\Delta_{ud}} \sim 4\,\text{TeV}, \quad M_{\Delta_{dd}} \sim 50\,\text{TeV}, \quad M_{\Delta_{uv}} \sim 1\,\text{TeV}, \quad \nu_{B-L} \sim 300\,\text{TeV} \]

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.
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, Heidenreinich (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,...)

![N-\bar{N} and BSM Physics](image)

(Fig. Courtesy of Yuri Kamshykov)
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.

\[
P(n - \bar{n})(t) = P(n - n')(t)P(n - \bar{n}')(t) \approx \left( \frac{t}{0.1 \text{ sec.}} \right)^4 \times 10^{-8}
\]

- This is a much higher probability for conventional oscillations:

\[
P(n - \bar{n}) \approx (t/0.1 \text{ sec})^2 \times 10^{-18}
\]

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

\[
H = \begin{pmatrix}
U_{n} + \Omega \sigma & 0 & \epsilon & \kappa \\
0 & U_{\bar{n}} - \Omega \sigma & \kappa & \epsilon \\
\epsilon & \kappa & U_{n'} + \Omega' \sigma & 0 \\
\kappa & \epsilon & 0 & U_{\bar{n}'} - \Omega' \sigma
\end{pmatrix}
\]
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:
  \[ \mathcal{L}_{LIV} = a_\mu \bar{n} \gamma^\mu n - i c_{\mu\nu} \bar{n} \gamma^\mu \partial^\nu n + h.c. \]

- When \( \langle a^0 \rangle \neq 0 \) and \( \langle c_{00} \rangle \neq 0 \) Lorentz violating couplings are induced:
  \[ \mathcal{L}_{LIV} = \delta_{LV}^{(1)} n^\dagger n - i \delta_{LV}^{(2)} n^\dagger \partial^0 n + h.c. \]

- \( \delta_{LV}^{(1)} \) inhibits free neutron oscillations, and could be bounded by \( \delta_{LV}^{(1)} < 10^{-23} \) GeV

- \( n - \bar{n} \) mixing Hamiltonian, after spin decomposition becomes (Gardner)

\[
M_{4 \times 4} = \begin{pmatrix}
    m + \delta_{LV}^{(1)} + m \delta_{LV}^{(2)} & \delta_{B=2} & 0 & 0 \\
    \delta_{B=2} & m - \delta_{LV}^{(1)} + m \delta_{LV}^{(2)} & 0 & 0 \\
    0 & 0 & m + \delta_{LV}^{(1)} + m \delta_{LV}^{(2)} & -\delta_{B=2} \\
    0 & 0 & -\delta_{B=2} & m - \delta_{LV}^{(1)} + m \delta_{LV}^{(2)}
\end{pmatrix}.
\]
Constraining long-range baryonic forces

- $\alpha_B$: strength of Yukawa potential; $R_0 = \text{Radius of Earth}$
- $R$: Range of new force

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

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