Neutron-Antineutron Conversion to Search for B-L Violation

($\bar{n}$-$n$ via scattering)

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Based, in part, on...

and on ongoing work in collaboration with Xinshuai Yan

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Perspective: Why Search for $\bar{n}$-$n$?

The origin of the neutrino mass is not yet known.

A massive neutrino can have a Dirac and/or Majorana mass.

If Dirac, then one can use the Higgs mechanism (after adding a new field: $\nu_R$).

If Majorana, a dimension five ($\text{B-L}$ violating!) mass term appears: \(\lambda (\nu_{\text{weak}}^2/\Lambda) \nu_L^T C \nu_L\) \cite{Weinberg, 1979}

If both mass types appear, the mass eigenstates would be Majorana \cite{Gribov and Pontecorvo, 1969; Bilenky and Pontecorvo, 1983}

$\rightarrow$ The neutrino is its own antiparticle

If $\text{B-L}$ is broken, then the “see-saw” mechanism can explain why $m_\nu$ is so small \cite{Minkowski, 1977; Gell-Mann, Ramond, & Slansky, 1979; Yanagida, 1980; Mohapatra & Senjanovic, 1980}
Mechanisms of 0ν ββ decay

Why the energy scale of B-L violation matters

If it is generated by the Weinberg operator, then SM electroweak symmetry yields $m_\nu = \frac{\lambda v^2_{\text{weak}}}{\Lambda}$. If $\lambda \sim 1$ and $\Lambda \gg v_{\text{weak}}$, then naturally $m_\nu \ll m_f$!

N.B. if $m_\nu \sim 0.2$ eV, then $\Lambda \sim 1.6 \times 10^9$ GeV!

Alternatively it could also be generated by higher dimension $|\Delta L| = 2$ operators, so that $m_\nu$ is small just because $d \gg 4$ and $\Lambda$ need not be so large.

[Effective Field Theories: Babu & Leung, 2001; de Gouvea & Jenkins, 2008 and many models]

Can we establish the scale of $B - L$ violation in another way?

N.B. searches for same sign dilepton final states at the LHC also constrain the higher dimension (“short range”) operators. [Helo, Kovalenko, Hirsch, and Päs, 2013]

Here we consider B-L violation in the quark sector: via $n - \bar{n}$ transitions

$\Lambda_{B-L} \sim 100$ TeV
Neutron-Antineutron Transitions

Can be realized in different ways

Enter searches for

- neutron-antineutron oscillations (free n’s & in nuclei)
  
  \[ M = \begin{pmatrix} M_n - \mu_n B & \delta \\ \delta & M_n + \mu_n B \end{pmatrix} \]

  \[ P_{n\rightarrow\bar{n}}(t) \simeq \frac{\delta^2}{2(\mu_n B)^2} \left[ 1 - \cos(2\mu_n B t) \right] \]

- dinucleon decay (in nuclei)
  (limited by finite nuclear density)

- neutron-antineutron conversion \(\text{(NEW!)}\)

Neutron-Antineutron Transitions

Some Novel Features

• Majorana C, P, and T phase constraints

Recall from neutrino physics: the discrete symmetry transformations of a theory should not depend on whether it contains Dirac or Majorana fields.

[Kayser and Goldhaber, 1983; Kayser, 1984 — also Carruthers, 1971; Feinberg and Weinberg, 1959]

Consequently the CPT, CP, and C phases of Majorana fields or states are restricted.

[Kayser and Goldhaber, 1983; Kayser, 1984]

Generalizing this to theories of fermions with B-L violation, the phases associated with the discrete symmetry transformations must themselves be restricted.

[SG and Yan, 2016]

• Incompatible with pure QCD in the isospin symmetry (but compatible with the SM!)

[SG & Xinshuai Yan, 2016: Carruthers, 1967….]
Dirac Fermions with B-L Violation

The prototypical $B - \mathcal{L}$ violating operator is of form
\[ \psi^T C \psi + \text{h.c.} \]
Since $C$ satisfies $(\sigma^{\mu\nu})^T C = -C\sigma^{\mu\nu}$, this operator is Lorentz invariant. Under CPT...

**unimodular phases:** $\eta_P \propto i$ ; $\eta_P \eta_C \eta_T \propto i$

\[
\begin{align*}
O_1 &= \psi^T C \psi + \text{h.c.} \\
O_2 &= \psi^T C \gamma^5 \psi + \text{h.c.} \\
O_3 &= \psi^T C \gamma^\mu \psi \partial^\nu F_{\mu\nu} + \text{h.c.} \\
O_4 &= \psi^T C \gamma^\mu \gamma^5 \psi \partial^\nu F_{\mu\nu} + \text{h.c.} \\
O_5 &= \psi^T C \sigma_{\mu\nu} \psi F^{\mu\nu} + \text{h.c.} \\
O_6 &= \psi^T C \sigma_{\mu\nu} \gamma^5 \psi F^{\mu\nu} + \text{h.c.}
\end{align*}
\]

CPT odd operators vanish from fermion antisymmetry

The phase constraint is crucial!

**Neutrinos:**

[Schechter and Valle, 1981; Nieves, 1982; Kayser, 1982; Shrock, 1982; Li and Wilczek, 1982; Davidson, Gorbahn, Santamaria, 2006]
Spin can play a role in a “mediated” process

A neutron-antineutron oscillation is a spontaneous process & thus the spin does not ever flip

However,

\[ O_4 = \psi^T C \gamma^\mu \gamma_5 \psi \partial^\nu F_{\mu \nu} + \text{h.c.} \]

\[ n(+) \rightarrow \bar{n}(-) \] occurs directly because the interaction with the current flips the spin.

This is concomitant with \[ n(p_1, s_1) + n(p_2, s_2) \rightarrow \gamma^*(k) \], for which only \( L = 1 \) and \( S = 1 \) is allowed via angular momentum conservation and Fermi statistics. [Berezhiani and Vainshtein, 2015]

Here \( e + n \rightarrow \bar{n} + e \), e.g., so that the experimental concept for “\( n\bar{n} \) conversion” would be completely different.
Neutron-Antineutron Conversion

Different mechanisms are possible

* $\eta - \bar{\eta}$ conversion and oscillation could share the same “TeV” scale BSM sources

Then the quark-level conversion operators can be derived noting the quarks carry electric charge

* $\eta - \bar{\eta}$ conversion and oscillation could come from different BSM sources

Then the neutron-level conversion operators could also be different

Note studies of scattering matrix elements of Majorana dark matter [Kumar & Marfatia, PRD, 2013]
Effective Lagrangian

Neutron interactions with B-L violation & electromagnetism

\[ \mathcal{L}_{\text{eff}} \supset -\frac{1}{2} \mu_n \bar{n} \sigma^{\mu\nu} n F_{\mu\nu} - \frac{\delta}{2} n^T C n - \frac{\eta}{2} n^T C \gamma^\mu \gamma^5 n j_\mu + \text{h.c.} \]

magnetic moment

\[ [ Q e j^\nu = \partial_\mu F^{\mu\nu} ] \]

"spontaneous" oscillation

Since the quarks carry electric charge, a BSM model that generates neutron-antineutron oscillations can also generate conversion

[SG & Xinshuai Yan, arXiv: 1710.09292]
Neutron-Antineutron Oscillation

Quark-level operators

\[(O_1)_{\chi_1 \chi_2 \chi_3} = [u^T_\chi_1 C u^\beta_\chi_1] [d^T_\chi_2 C d^\delta_\chi_2] [d^T_\chi_3 C d^\sigma_\chi_3] (T_s)_{\alpha \beta \gamma \delta \rho \sigma},\]

\[(O_2)_{\chi_1 \chi_2 \chi_3} = [u^T_\chi_1 C d^\beta_\chi_1] [u^T_\chi_2 C d^\delta_\chi_2] [d^T_\chi_3 C d^\sigma_\chi_3] (T_s)_{\alpha \beta \gamma \delta \rho \sigma},\]

\[(T_s)_{\alpha \beta \gamma \delta \rho \sigma} = \epsilon_{\rho \alpha \gamma} \epsilon_{\sigma \beta \delta} + \epsilon_{\sigma \alpha \gamma} \epsilon_{\rho \beta \delta} + \epsilon_{\rho \beta \gamma} \epsilon_{\sigma \alpha \delta} + \epsilon_{\sigma \beta \gamma} \epsilon_{\rho \alpha \delta},\]

\[(T_a)_{\alpha \beta \gamma \delta \rho \sigma} = \epsilon_{\rho \alpha \beta} \epsilon_{\sigma \gamma \delta} + \epsilon_{\sigma \alpha \beta} \epsilon_{\rho \gamma \delta}\]

Only 14 of 24 operators are independent

\[(O_1)_{\chi_1 LR} = (O_1)_{\chi_1 RL}, \quad (O_{2,3})_{LR\chi_3} = (O_{2,3})_{RL\chi_3},\]

\[(O_2)_{mmn} - (O_1)_{mmn} = 3(O_3)_{mmn} \quad [Caswell, Milutinovic, & Senjanovic, 1983]\]
From Oscillation to Conversion

**Quark-level operators:** compute \( q^\rho(p) + \gamma(k) \rightarrow \bar{q}^\delta(p') \)

\[
\mathcal{H}_I \supset \frac{\delta_q}{2} \sum_{\chi_1} (\psi_{\chi_1}^\rho C \psi_{\chi_1}^\delta + \bar{\psi}_{\chi_1}^\delta C \bar{\psi}_{\chi_1}^\rho) + Q_\rho e \sum_{\chi_2} \bar{\psi}_{\chi_2}^\rho A \psi_{\chi_2}^\rho \\
+ Q_\delta e \sum_{\chi_3} \bar{\psi}_{\chi_3}^\delta A \psi_{\chi_3}^\delta,
\]

matrix element:

\[
\left\langle \bar{q}^\delta(p') \right| T \left( \sum_{\chi_1, \chi_2} \left( -i \frac{\delta_q}{2} \int d^4 x \psi_{\chi_1}^{\rho T} C \psi_{\chi_1}^\delta \right) \right. \\
\times \left. \left( -i Q_\rho e \int d^4 y \bar{\psi}_{\chi_2}^\rho A \psi_{\chi_2}^\rho - i Q_\delta e \int d^4 y \bar{\psi}_{\chi_2}^\delta A \psi_{\chi_2}^\delta \right) \right) \\
\times \left| q^\rho(p) \gamma(k) \right\rangle,
\]

**Effective vertex**

\[
- \frac{m \delta_q e}{p^2 - m^2} (Q_\rho \psi_{-\chi_2}^\delta C \gamma^\mu \psi_{\chi_2}^\rho - Q_\delta \psi_{\chi_2}^\delta C \gamma^\mu \psi_{-\chi_2}^\rho),
\]

if \( \delta = \rho \)
yields

\( C \gamma_\mu \gamma_5 \) only
B-L Violation via e-n scattering

Linking neutron-antineutron oscillation to conversion

\[
(\mathcal{O}_2)_{\chi_1 \chi_2 \chi_3} = \left[ u_{\chi_1}^T C d_{\chi_1}^\beta \right] \left[ u_{\chi_2}^T C d_{\chi_2}^\delta \right] \left[ d_{\chi_3}^T C d_{\chi_3}^\sigma \right] (T_s)_{\alpha \beta \gamma \delta \rho \sigma}
\]

[Rao & Shrock, 1983]

e.g.:

\[
(\tilde{\mathcal{O}}_2)_{\chi_1 \chi_2 \chi_3} = \left[ u_{-\chi}^T C \gamma^\mu \gamma^5 d_{\chi}^\beta - 2 u_{\chi}^T C \gamma^\mu \gamma^5 d_{-\chi}^\beta \right] \left[ u_{\chi_2}^T C d_{\chi_2}^\delta \right] \left[ d_{\chi_3}^T C d_{\chi_3}^\sigma \right] + \left[ u_{\chi_1}^T C d_{\chi_1}^\beta \right] \left[ u_{-\chi}^T C \gamma^\mu \gamma^5 d_{\chi}^\delta - 2 u_{\chi}^T C \gamma^\mu \gamma^5 d_{-\chi}^\delta \right] \left[ d_{\chi_3}^T C d_{\chi_3}^\sigma \right] + \left[ u_{\chi_1}^T C d_{\chi_1}^\beta \right] \left[ u_{\chi_2}^T C d_{\chi_2}^\delta \right] \left[ d_{-\chi}^T C \gamma^\mu \gamma^5 d_{\chi}^\sigma + d_{\chi}^T C \gamma^\mu \gamma^5 d_{-\chi}^\sigma \right] T_s...
\]
B-L Violation via e-n scattering
Linking neutron-antineutron oscillation to conversion

Moreover...

\[(\tilde{O}_1)^{\chi \mu}_{\chi_1 \chi_2 \chi_3} = \left[ -2[u^T_{-\chi} C \gamma^\mu \gamma_5 u^\beta_{-\chi} + u^T_{\chi} C \gamma^\mu \gamma_5 u^\beta_{-\chi}]\left[d^\gamma_{\chi_2} C d^\delta_{\chi_2}\right][d^\rho_{\chi_3} C d^\sigma_{\chi_3}] + [u^T_{\chi_1} C u^\beta_{\chi_1}]\left[d^\gamma_{-\chi} C \gamma^\mu \gamma_5 d^\delta_{-\chi} + d^\gamma_{\chi} C \gamma^\mu \gamma_5 d^\delta_{-\chi}\right][d^\rho_{\chi_3} C d^\sigma_{\chi_3}] + [u^T_{\chi_1} C u^\beta_{\chi_1}]\left[d^\gamma_{\chi_2} C d^\delta_{\chi_2}\right]\left[d^\rho_{-\chi} C \gamma^\mu \gamma_5 d^\sigma_{-\chi} + d^\rho_{\chi} C \gamma^\mu \gamma_5 d^\sigma_{-\chi}\right]\right](T_s)_{\alpha \beta \gamma \delta \rho \sigma}\]

yielding [Here \(\chi=R-\chi=L\) for em scattering]

\[(\tilde{O}_1)^{\chi}_{\chi_1 \chi_2 \chi_3} = (\delta_1)_{\chi_1 \chi_2 \chi_3} \frac{em}{3(p_{\text{eff}}^2 - m^2)} \frac{Q e j_\mu}{q^2} \frac{Q e j_\mu}{q^2} (\tilde{O}_1)^{\chi \mu}_{\chi_1 \chi_2 \chi_3},\]

with similar relationships for \(i=2,3\) [only these in em case]

The hadronic matrix elements are computed in the MIT bag model.
B-L Violation via e-d scattering

What sorts of limits could be set?

Matching relation:

$$
\eta \bar{\nu}(p', s') C f \gamma_5 u(p, s) = \frac{e m}{3(p_{\text{eff}}^2 - m^2)} \frac{e j_\mu}{q^2}
$$

$$
\times \langle \bar{n}_q(p', s') | \int d^3 x \sum_{i,\chi_1, \chi_2, \chi_3} ^{'} (\delta_i)_{\chi_1, \chi_2, \chi_3} [(\tilde{O}_i)^{R,\mu}_{\chi_1, \chi_2, \chi_3} - (\tilde{O}_i)^{L,\mu}_{\chi_1, \chi_2, \chi_3}] | n_q(p, s) \rangle
$$

The best limits come from small-angle scattering — using the uncertainty principle to estimate $\theta_{\text{min}}$

Sensitivity estimate for a beam energy of 20 MeV:

$$
|\tilde{\delta}| \lesssim 2 \times 10^{-15} \sqrt{\frac{N \text{ events}}{1 \text{ event}}} \sqrt{\frac{1 \text{ yr}}{t}} \sqrt{\frac{0.6 \times 10^{17} \text{ s}^{-1}}{\phi}} \sqrt{\frac{1 \text{ m}}{L}} \sqrt{\frac{5.1 \times 10^{22} \text{ cm}^{-3}}{\rho}} \text{ GeV.}
$$

for the Majorana mass of the neutron
B-L Violation via n-d scattering

What sorts of limits could be set?

For cold neutrons (as at the ILL)

$$|p_n| = 1.94 \text{ keV}$$

Sensitivity estimate (set by n-e scattering):

$$|\delta| \lesssim 3 \times 10^{-19} \sqrt{\frac{N \text{ events}}{1 \text{ event}}} \sqrt{\frac{1 \text{ yr}}{t}} \sqrt{\frac{1.7 \times 10^{11} \text{ s}^{-1}}{\phi}} \sqrt{\frac{1 \text{ m}}{L}} \sqrt{\frac{5 \times 10^{22} \text{ cm}^{-3}}{\rho}} \text{ GeV}$$

for the Majorana mass of the neutron

The combination of e and n beam experiments should offer a powerful crosscheck
We are studying how the best experimental paths change if conversion and oscillation stem from different new physics sources.
The discovery of B-L violation would reveal the existence of dynamics beyond the Standard Model.

The energy scale of B-L violation speaks to different explanations as to why the neutrino is light (A “TeV scale” mechanism could also generate B-L violation in the quark sector).

We have discussed neutron-antineutron conversion, i.e., neutron-antineutron transitions as mediated by an external current (as via scattering).

Neutron-antineutron conversion is not sensitive to medium effects and can also yield limits on the neutron’s Majorana mass. It can also lead to the discovery of B-L violation in its own right.

Experiments with intense low-energy electron or neutron beams can also be used to search for B-L violation.
Backup Slides
Neutron-Antineutron Transitions

C, P, & T Phase Constraints

For any fermion field

\[
\begin{align*}
C\psi(x)C^{-1} &= \eta_c C \gamma^0 \psi^*(x) \equiv \eta_c i \gamma^2 \psi^*(x) \equiv \eta_c \psi^c(x), \\
P\psi(t, x)P^{-1} &= \eta_p \gamma^0 \psi(t, -x), \\
T\psi(t, x)T^{-1} &= \eta_t \gamma^3 \psi(-t, x),
\end{align*}
\]

Thus \(P^2 \psi(x)P^{-2} = \eta_p^2 \psi(x)\) but \(C^2 \psi(x)C^{-2} = \psi(x); T^2 \psi(x)T^{-2} = -\psi(x)\)

The plane wave expansion of a general Majorana field \(\psi_m\) is

\[
\psi_m(x) = \int \frac{d^3p}{(2\pi)^{3/2} \sqrt{2E}} \sum_s \{ f(p, s)u(p, s)e^{-ip \cdot x} + \lambda f^\dagger(p, s)v(p, s)e^{ip \cdot x} \}
\]

Applying \(C\) and noting the Majorana relation,

\[
i \gamma^2 \psi^*_m(x) = \lambda^* \psi_m(x)
\]

yields

\[
C\psi_m(x)C^{-1} = \eta_c \lambda^* \psi_m(x)
\]

\[
Cf(p, s)C^{-1} = \eta_c \lambda^* f(p, s) \quad \text{and} \quad Cf^\dagger(p, s)C^{-1} = \eta_c \lambda^* f^\dagger(p, s)
\]

Since \(C\) is a unitary operator, taking the adjoint shows \(\eta_c^* \lambda\) is real.
C, P, & T Phase Constraints

Under CP, we find $\eta_p^* \eta_c^* \lambda$ is imaginary, or that $\eta_p^*$ is imaginary.

Under T we find that $\eta_t \lambda$ is real, whereas

$$\text{CPT}\psi_m(x)(\text{CPT})^{-1} = -\eta_c \eta_p \eta_t \gamma^5 \psi_m^*(-x)$$

yielding

$$\text{CPT}f(p, s)(\text{CPT})^{-1} = s\lambda^* \eta_c \eta_p \eta_t f(p, -s)$$

$$\text{CPT}f^\dagger(p, s)(\text{CPT})^{-1} = -s\lambda \eta_c \eta_p \eta_t f^\dagger(p, -s)$$

Since $\text{CPT}$ is antiunitary, $\text{CPT} = KU_{cpt}$, where $U_{cpt}$ denotes a unitarity operator.

We conclude $\eta_c \eta_p \eta_t$ is pure imaginary.

Since $\eta_p$ is imaginary, $\eta_c \eta_t$ must also be real — but $\eta_c \eta_p$ itself is unconstrained.

Since the phases are unimodular, they impact the discrete symmetry transformation properties of $B-L$ violating operators only.

Building a Majorana field from Dirac fields yields

$$\psi_{m\pm}(x) = \frac{1}{\sqrt{2}}(\psi(x) \pm C\psi(x)C^{-1})$$

and $\lambda = \pm \eta_c$; all our other conclusions emerge as well.

$$\eta_p \propto i \quad ; \quad \eta_p \eta C \eta T \propto i$$
\(n - \bar{n}\) & Nuclear Stability

\(n-\bar{n}\) oscillations can be studied in bound or free systems.

New limits on dinucleon decay in nuclei have also recently been established.

\[\begin{align*}
16\text{O}(pp) &\rightarrow 14\text{C} \pi^+ \pi^+ \text{ has } \tau > 7.22 \times 10^{31} \text{ years at 90\% CL.} \\
16\text{O}(pn) &\rightarrow 14\text{N} \pi^+ \pi^0 \text{ has } \tau > 1.70 \times 10^{32} \text{ years at 90\% CL.} \\
16\text{O}(nn) &\rightarrow 14\text{O} \pi^0 \pi^0 \text{ has } \tau > 4.04 \times 10^{32} \text{ years at 90\% CL.}
\end{align*}\]

Note \(\tau_{NN} = T_{\text{nuc}} \tau_{n\bar{n}}^2\) with \(T_{\text{nuc}} \sim 1.1 \times 10^{25} \text{s}^{-1}\)

Large suppression factors appear in all such nuclear studies, making free searches more effective. (at first glance)

In the case of bound \(n-\bar{n}\) the suppression is set by

\[\frac{\delta^2}{(V_n - V_{\bar{n}})^2}\]

the difference in nuclear optical potentials. [Dover, Gal, and Richard; Friedman and Gal, 2008]

Now \(16\text{O}(n-\bar{n})\) has \(\tau > 1.9 \times 10^{32} \text{ years at 90\% CL,} \)
yielding \(\tau_{n\bar{n}} > 2.7 \times 10^8 \text{ s.} \) [Abe et al., Super-K Collaboration, arXiv:1109.4227.]

Cf. free limit: \(\tau_{n\bar{n}} \geq 0.85 \times 10^8 \text{ s at 90\% C.L.} \) [Baldo-Ceolin et al., ZPC, 1994 (ILL)]

with future improvements expected.

The nuclear suppression dwarfs that from magnetic fields.
B-L Violation & Self-Conjugate Fermions

In attempting to rationalize the spectral pattern of the low-lying, light hadrons, Carruthers discovered a class of theories for which the CPT theorem does not hold. [Carruthers, 1967]

The pions form a self-conjugate isospin multiplet \((\pi^+, \pi^0, \pi^-)\), but the kaons form pair-conjugate multiplets \((K^+, K^0)\) and \((\bar{K}^0, K^-)\).

Carruthers discovered that free theories of self-conjugate bosons with half-integer isospin are nonlocal, that the commutator of two self-conjugate fields with opposite isospin components do not vanish at space-like separations. [Carruthers, 1967]

Moreover, since weak local communitivity fails, CPT symmetry is no longer expected to hold, nor should the CPT theorem of Greenberg apply. [Carruthers, 1968; Streater and Wightman, 2000; Greenberg, 2002]

The neutron and antineutron are members of pair-conjugate \(I = 1/2\) multiplets. The quark-level operators that generate \(n - \bar{n}\) oscillations would also produce \(p - \bar{p}\) oscillations under the isospin transformation \(u \leftrightarrow d\), though the latter are removed by electric charge conservation....

Ergo \(n-\bar{n}\) oscillations are problematic in pure QCD in the isospin limit. [SG and Yan, 2016]


B-L Violation & $n-\bar{n}$ Transitions

It has long been thought that $n-\bar{n}$ oscillations could shed light on the mechanism of

- Baryogenesis [Kuzmin, 1967]
- Neutrino mass [Mohapatra and Marshak, 1980]

The observation of $n-\bar{n}$ transformations would reveal that $B - \mathcal{L}$ is indeed broken.

Extracting the scale of $B - \mathcal{L}$ breaking from such a result can be realized through a matrix element computation in lattice QCD. There has been much progress towards this goal.

[Buchoff, Schroeder, and Wasem, 2012; Buchoff and Wagman, 2016; Syritsen, Buchoff, Schroeder, and Wasem, 2016]

In contrast to proton decay, $n-\bar{n}$ probes new physics at “intermediate” energy scales. The two processes can be generated by $d=6$ and $d=9$ operators, respectively.

Crudely, $\Lambda_{p\text{decay}} \geq 10^{15}$ GeV and $\Lambda_{n\bar{n}} \geq 10^{5.5}$ GeV.

Observing a neutron-antineutron transition would show that B-L violation does exists at an intermediate (~100 TeV) scale…. 
Why Search for $n - \bar{n}$?

The Standard Model (SM) cannot explain the origin of the cosmic baryon asymmetry, dark matter, or dark energy.

B violation plays a role in at least one of these puzzles.

Although B violation appears in the SM (sphalerons),

[Kuzmin, Rubakov, & Shaposhnikov, 1985]

we know nothing of its pattern at accessible energies.

Do processes occur with $|\Delta B| = 1$ or $|\Delta B| = 2$ or both?


The SM conserves B-L, but does Nature?

If neutron-antineutron oscillations, e.g., are observed, then B-L is broken, and we have found physics BSM!