Neutron-Antineutron Conversion to Search for B-L Violation

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

Susan Gardner

Department of Physics and Astronomy
University of Kentucky
Lexington, KY

Based, in part, on...
S.G. & Xinshuai Yan (U. Kentucky), Phys. Rev. D93, 096008 (2016) [arXiv:1602.00693];
S.G. & Xinshuai Yan, Phys. Rev. D97, 056008 (2018) [arXiv:1710.09292];
and on ongoing work in collaboration with Xinshuai Yan

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

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: ν_R)

If Majorana, a dimension five (B-L violating!) mass term appears ($\lambda(v_{\rm weak}^2/\Lambda)\nu_L^T C \nu_L$) [Weinberg, 1979]

If both mass types appear, the mass eigenstates would be Majorana [Gribov and Pontecorvo, 1969; Bilenky and Pontecorvo, 1983]

→ **The neutrino is its own antiparticle**

If B-L is broken, then the "see-saw" mechanism can explain why m_ν is so small [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 $m_\nu = \lambda v_{\rm weak}^2/\Lambda$. If $\lambda \sim 1$ and $\Lambda \gg v_{\rm weak}$, 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_ν is small just because $d \gg 4$ and Λ need not be so large.

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

Can we establish the scale of $\mathcal{B} - \mathcal{L}$ 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-$\bar{\rm n}$ transitions

→ $\Lambda_{\rm B\text{-}L} \sim 100$ TeV

Neutron-Antineutron Transitions

Can be realized in different ways

Enter searches for

- neutron-antineutron oscillations (free n's & in nuclei)

"spontaneous"
& thus sensitive to
environment

$$\mathcal{M} = \begin{pmatrix} M_n - \mu_n B & \delta \\ \delta & M_n + \mu_n B \end{pmatrix}$$

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

- dinucleon decay (in nuclei)
  (limited by finite nuclear density)
- neutron-antineutron conversion (NEW!)

[SG & Xinshuai Yan, arXiv:1710.09292, PRD 2018 (also arXiv:1602.00693, PRD 2016)]

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

Constraints on unimodular phase in P, CT, and CPT!

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

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

$$\mathcal{O}_1 = \psi^T C\psi + \text{h.c.} \quad \overset{\textbf{CPT}}{\Longrightarrow} \quad -(\eta_c\eta_p\eta_t)^2 \quad \rightarrow \quad +1$$

$$\mathcal{O}_2 = \psi^T C\gamma_5\psi + \text{h.c.} \quad \overset{\textbf{CPT}}{\Longrightarrow} \quad -(\eta_c\eta_p\eta_t)^2$$

$$\mathcal{O}_3 = \psi^T C\gamma^\mu\psi\,\partial^\nu F_{\mu\nu} + \text{h.c.} \quad \overset{\textbf{CPT}}{\Longrightarrow} \quad +(\eta_c\eta_p\eta_t)^2 \quad ✖$$

$$\mathcal{O}_4 = \psi^T C\gamma^\mu\gamma_5\psi\,\partial^\nu F_{\mu\nu} + \text{h.c.} \quad \overset{\textbf{CPT}}{\Longrightarrow} \quad -(\eta_c\eta_p\eta_t)^2$$

$$\mathcal{O}_5 = \psi^T C\sigma_{\mu\nu}\psi\, F^{\mu\nu} + \text{h.c.} \quad \overset{\textbf{CPT}}{\Longrightarrow} \quad +(\eta_c\eta_p\eta_t)^2 \quad ✖$$

$$\mathcal{O}_6 = \psi^T C\sigma_{\mu\nu}\gamma_5\psi\, F^{\mu\nu} + \text{h.c.} \quad \overset{\textbf{CPT}}{\Longrightarrow} \quad +(\eta_c\eta_p\eta_t)^2 \quad ✖$$

The phase constraint is crucial!

CPT odd operators vanish from fermion antisymmetry

Neutrinos: [Schechter and Valle, 1981; Nieves, 1982; Kayser, 1982; Shrock, 1982; Li and Wilczek, 1982; Davidson, Gorbahn, Santamaria, 2006]

n - n̄ Transitions & Spin

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,

$$\mathcal{O}_4 = \psi^T C\gamma^\mu \gamma_5 \psi \, \partial^\nu F_{\mu\nu} + \text{h.c.}$$

$n(+) \to \bar{n}(-)$ occurs directly because the interaction with the current flips the spin.

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

Here $e + n \to \bar{n} + e$, e.g., so that the experimental concept for "$n\bar{n}$ conversion" would be completely different.

Neutron-Antineutron Conversion

Different mechanisms are possible

* n-n̄ 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

* n-n̄ 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

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

$[\, Qej^\nu = \partial_\mu F^{\mu\nu} \,]$

magnetic moment

$n \to \bar{n}$ oscillation

$n \to \bar{n}$ conversion

"spontaneous" → oscillation

[SG & Xinshuai Yan, arXiv: 1710.09292]

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

Neutron-Antineutron Oscillation

Quark-level operators

[Rao & Shrock, 1982]

$$(\mathcal{O}_1)_{\chi_1\chi_2\chi_3} = [u^{T\alpha}_{\chi_1} C u^{\beta}_{\chi_1}][d^{T\gamma}_{\chi_2} C d^{\delta}_{\chi_2}][d^{T\rho}_{\chi_3} C d^{\sigma}_{\chi_3}](T_s)_{\alpha\beta\gamma\delta\rho\sigma},$$

$$(\mathcal{O}_2)_{\chi_1\chi_2\chi_3} = [u^{T\alpha}_{\chi_1} C d^{\beta}_{\chi_1}][u^{T\gamma}_{\chi_2} C d^{\delta}_{\chi_2}][d^{T\rho}_{\chi_3} C d^{\sigma}_{\chi_3}](T_s)_{\alpha\beta\gamma\delta\rho\sigma},$$

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

Note

$O_2 \to O_3$

$T_s \to T_a$

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

- Only 14 of 24 operators are independent

$$(\mathcal{O}_1)_{\chi_1 LR} = (\mathcal{O}_1)_{\chi_1 RL}, \qquad (\mathcal{O}_{2,3})_{LR\chi_3} = (\mathcal{O}_{2,3})_{RL\chi_3},$$

$$(\mathcal{O}_2)_{mmn} - (\mathcal{O}_1)_{mmn} = 3(\mathcal{O}_3)_{mmn}$$

[Caswell, Milutinovic, & Senjanovic, 1983]

From Oscillation to Conversion

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

$$\mathcal{H}_I \supset \frac{\delta_q}{2}\sum_{\chi_1}(\psi^{\rho T}_{\chi_1} C\psi^\delta_{\chi_1} + \bar{\psi}^\delta_{\chi_1} C\bar{\psi}^{\rho T}_{\chi_1}) + Q_\rho e\sum_{\chi_2}\bar{\psi}^\rho_{\chi_2}\not{A}\psi^\rho_{\chi_2}$$
$$+ Q_\delta e\sum_{\chi_3}\bar{\psi}^\delta_{\chi_3}\not{A}\psi^\delta_{\chi_3},$$

flavor

chiral basis

matrix element:

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

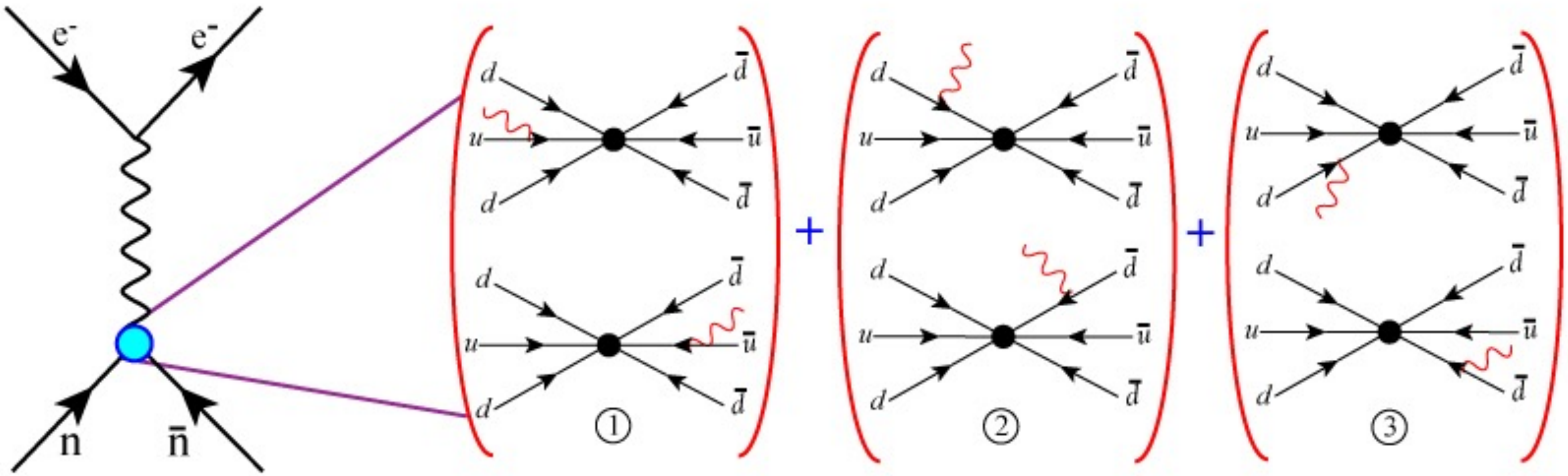
✿ if $\delta=\rho$ yields $C\gamma_\mu\gamma_5$ only

Effective vertex

$$-\frac{m\delta_q e}{p^2-m^2}(Q_\rho\psi^{\delta T}_{-\chi_2}C\gamma^\mu\psi^\rho_{\chi_2} - Q_\delta\psi^{\delta T}_{\chi_2}C\gamma^\mu\psi^\rho_{-\chi_2}),$$

B-L Violation via e-n scattering

Linking neutron-antineutron oscillation to conversion



e.g.:

$$(\mathcal{O}_2)_{\chi_1\chi_2\chi_3} = [u^{T\alpha}_{\chi_1} C d^{\beta}_{\chi_1}][u^{T\gamma}_{\chi_2} C d^{\delta}_{\chi_2}][d^{T\rho}_{\chi_3} C d^{\sigma}_{\chi_3}](T_s)_{\alpha\beta\gamma\delta\rho\sigma}$$

[Rao & Shrock, 1983]

$$(\tilde{\mathcal{O}}_2)^{\chi\,\mu}_{\chi_1\chi_2\chi_3} = \Big[[u^{\alpha\,T}_{-\chi} C\gamma^{\mu}\gamma_5 d^{\beta}_{\chi} - 2u^{\alpha\,T}_{\chi} C\gamma^{\mu}\gamma_5 d^{\beta}_{-\chi}][u^{\gamma\,T}_{\chi_2} C d^{\delta}_{\chi_2}][d^{\rho\,T}_{\chi_3} C d^{\sigma}_{\chi_3}]$$
$$+[u^{\alpha\,T}_{\chi_1} C d^{\beta}_{\chi_1}][u^{\gamma\,T}_{-\chi} C\gamma^{\mu}\gamma_5 d^{\delta}_{\chi} - 2u^{\gamma\,T}_{\chi} C\gamma^{\mu}\gamma_5 d^{\delta}_{-\chi}][d^{\rho\,T}_{\chi_3} C d^{\sigma}_{\chi_3}]$$
$$+[u^{\alpha\,T}_{\chi_1} C d^{\beta}_{\chi_1}][u^{\gamma\,T}_{\chi_2} C d^{\delta}_{\chi_2}][d^{\rho\,T}_{-\chi} C\gamma^{\mu}\gamma_5 d^{\sigma}_{\chi} + d^{\rho\,T}_{\chi} C\gamma^{\mu}\gamma_5 d^{\sigma}_{-\chi}]\Big] T_s \ldots$$

B-L Violation via e-n scattering

Linking neutron-antineutron oscillation to conversion

Moreover…

$$
\begin{aligned}
(\tilde{\mathcal{O}}_1)^{\chi\,\mu}_{\chi_1\chi_2\chi_3} = & \Big[-2[u^{\alpha\,T}_{-\chi} C\gamma^\mu\gamma_5 u^\beta_\chi + u^{\alpha\,T}_{\chi} C\gamma^\mu\gamma_5 u^\beta_{-\chi}][d^{\gamma\,T}_{\chi_2} C d^\delta_{\chi_2}][d^{\rho\,T}_{\chi_3} C d^\sigma_{\chi_3}] \\
+ & [u^{\alpha\,T}_{\chi_1} C u^\beta_{\chi_1}][d^{\gamma\,T}_{-\chi} C\gamma^\mu\gamma_5 d^\delta_\chi + d^{\gamma\,T}_{\chi} C\gamma^\mu\gamma_5 d^\delta_{-\chi}][d^{\rho\,T}_{\chi_3} C d^\sigma_{\chi_3}] \\
+ & [u^{\alpha\,T}_{\chi_1} C u^\beta_{\chi_1}][d^{\gamma\,T}_{\chi_2} C d^\delta_{\chi_2}][d^{\rho\,T}_{-\chi} C\gamma^\mu\gamma_5 d^\sigma_\chi + d^{\rho\,T}_{\chi} C\gamma^\mu\gamma_5 d^\sigma_{-\chi}]\Big] (T_s)_{\alpha\beta\gamma\delta\rho\sigma}
\end{aligned}
$$

yielding [Here χ=R-χ=L for em scattering]

$$
(\tilde{\mathcal{O}}_1)^{\chi}_{\chi_1\chi_2\chi_3} = (\delta_1)_{\chi_1\chi_2\chi_3} \frac{em}{3(p^2_{\rm eff} - m^2)} \frac{Qej_\mu}{q^2} (\tilde{\mathcal{O}}_1)^{\chi\,\mu}_{\chi_1\chi_2\chi_3} \,,
$$

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:

$$\eta \bar{v}(\mathbf{p}', s') C \not{j} \gamma_5 u(\mathbf{p}, s) = \frac{em}{3(p_{\rm eff}^2 - m^2)} \frac{e j_\mu}{q^2}$$

$$\times \langle \bar{n}_{\rm q}(\mathbf{p}', \mathbf{s}')| \int \mathbf{d^3x} \sum_{\mathbf{i},\chi_1,\chi_2,\chi_3}{}' (\delta_{\mathbf{i}})_{\chi_1,\chi_2,\chi_3} [(\tilde{\mathcal{O}}_{\mathbf{i}})^{\rm R\,\mu}_{\chi_1,\chi_2,\chi_3} - (\tilde{\mathcal{O}}_{\mathbf{i}})^{\rm L\,\mu}_{\chi_1,\chi_2,\chi_3}] |\mathbf{n}_{\rm q}(\mathbf{p}, \mathbf{s})\rangle$$

The best limits come from small-angle scattering

— using the uncertainty principle to estimate $\theta_{\rm min}$

Sensitivity estimate for a beam energy of 20 MeV:

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

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)

$$|\boldsymbol{p}_n| = 1.94 \text{ keV}$$

Sensitivity estimate (set by n-e scattering):

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

for the Majorana mass of the neutron

The combination of e and n beam experiments should offer a powerful crosscheck

Ongoing Work

We are studying
how the best experimental paths
change if conversion and oscillation
stem from different
new physics sources

Summary

- 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

$$\mathbf{C}\psi(x)\mathbf{C}^{-1} = \eta_c C\gamma^0\psi^*(x) \equiv \eta_c i\gamma^2\psi^*(x) \equiv \eta_c\psi^c(x)\,,$$
$$\mathbf{P}\psi(t,\mathbf{x})\mathbf{P}^{-1} = \eta_p\gamma^0\psi(t,-\mathbf{x})\,,$$
$$\mathbf{T}\psi(t,\mathbf{x})\mathbf{T}^{-1} = \eta_t\gamma^1\gamma^3\psi(-t,\mathbf{x})\,,$$

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

The plane wave expansion of a general Majorana field ψ_m is

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

Applying C and noting the Majorana relation,

$$i\gamma^2\psi_m^*(x) = \lambda^*\psi_m(x)$$

yields

$$\mathbf{C}\psi_m(x)\mathbf{C}^{-1} \quad = \quad \eta_c\lambda^*\psi_m(x)$$

$\mathbf{C}f(\mathbf{p},s)\mathbf{C}^{-1} = \eta_c\lambda^* f(\mathbf{p},s)$ and $\mathbf{C}f^\dagger(\mathbf{p},s)\mathbf{C}^{-1} = \eta_c\lambda^* f^\dagger(\mathbf{p},s)$

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 η_p^* is imaginary.

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

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

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

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

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

Since η_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 $\mathcal{B}$-$\mathcal{L}$ violating operators only.

Building a Majorana field from Dirac fields yields $\psi_{m\pm}(x) = \frac{1}{\sqrt{2}}(\psi(x) \pm \mathbf{C}\psi(x)\mathbf{C}^{-1})$ and $\lambda = \pm\eta_c$; all our other conclusions emerge as well.

→ $\eta_P \propto i$; $\eta_P \eta_C \eta_T \propto i$

n - n̄ & Nuclear Stability

***n*-*n̄* oscillations can be studied in bound or free systems.**

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

[Gustafson et al., Super-K Collaboration, arXiv:1504.0104.]

$^{16}\mathrm{O}(pp) \to ^{14}\mathrm{C}\,\pi^+\pi^+$ has $\tau > 7.22 \times 10^{31}$ years at 90% CL.
$^{16}\mathrm{O}(pn) \to ^{14}\mathrm{N}\,\pi^+\pi^0$ has $\tau > 1.70 \times 10^{32}$ years at 90% CL.
$^{16}\mathrm{O}(nn) \to ^{14}\mathrm{O}\,\pi^0\pi^0$ has $\tau > 4.04 \times 10^{32}$ years at 90% CL.
Note $\tau_{NN} = T_{\rm nuc}\tau^2_{n\bar{n}}$ with $T_{\rm nuc} \sim 1.1 \times 10^{25}\mathrm{s}^{-1}$

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

In the case of bound *n*-*n̄* 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 $^{16}\mathrm{O}(n{-}\bar{n})$ has $\tau > 1.9 \times 10^{32}$ years at 90% CL,
yielding $\tau_{n\bar{n}} > 2.7 \times 10^8$ s. [Abe et al., Super-K Collaboration, arXiv:1109.4227.]

Cf. free limit: $\tau_{n\bar{n}} \geq 0.85 \times 10^8\,\mathrm{s}$ 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 (π^+, π^0, π^-), 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 $\mathcal{B} - \mathcal{L}$ is indeed broken.

Extracting the scale of $\mathcal{B} - \mathcal{L}$ 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, $\Lambda_{p\,decay} \geq 10^{15}\,\mathrm{GeV}$ and $\Lambda_{n\bar{n}} \geq 10^{5.5}\,\mathrm{GeV}$.

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?
[Marshak and Mohapatra, 1980; Babu & Mohapatra, 2001 & 2012; Arnold, Fornal, & Wise, 2013]
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!