$n - \bar{n}$ Oscillations: Some Phenomenology and a Theoretical Model

Robert Shrock

YITP, Stony Brook University

Intensity Frontier Workshop, Argonne National Lab, 4/25/2013

Outline

- Theoretical motivations for $n - \bar{n}$ oscillations

- General formalism and current experimental limits

- Operator analysis and estimate of matrix elements

- Calculation of $n - \bar{n}$ oscillations in an extra-dimensional model

- Conclusions: our model is an example of how $n - \bar{n}$ oscillations can occur at rates comparable to current limits, providing motivation for a more sensitive experimental search as part of US Intensity Frontier Program.

Theoretical Motivations

- Producing the observed baryon asymmetry in the universe requires interactions that violate baryon number, B (Sakharov, 1967).
- General phenomenological possibility of baryon number violation via the $|\Delta B| = 2$ process $n \leftrightarrow \bar{n}$ (Kuzmin, 1970).
- Since (anti)quarks and (anti)leptons are placed in same representations in grand unified theories (GUT's), the violation of B and L is natural in these theories. Besides proton decay, $n - \bar{n}$ oscillations can occur (Glashow, 1979; Marshak and Mohapatra, 1980). Calculation of six-quark matrix elements for $n - \bar{n}$ transitions (Rao and Shrock, 1982).
- Some sources of recent interest in $n - \bar{n}$ oscillations
  - in some specific supersymmetric and nonsupersymmetric models (talks by Babu and Mohapatra)
  - in an extra-dimension model (Nussinov and Shrock, PRL 88, 171601 (2002)) with $n - \bar{n}$ oscillations at a rate comparable to current limit

General Formalism

$n - \bar{n}$ Oscillations in Field-Free Vacuum:

$\langle n|H_{eff}|n\rangle = \langle\bar{n}|H_{eff}|\bar{n}\rangle = m_n - i\lambda/2$, where H_{eff} denotes relevant Hamiltonian and $\lambda^{-1} = \tau_n = 0.88 \times 10^3$ sec. H_{eff} may also mediate $n \leftrightarrow \bar{n}$ transitions: $\langle\bar{n}|H_{eff}|n\rangle \equiv \delta m$. Consider the 2×2 matrix

$$\mathcal{M} = \begin{pmatrix} m_n - i\lambda/2 & \delta m \\ \delta m & m_n - i\lambda/2 \end{pmatrix}$$

Diagonalizing $\mathcal{M}$ yields mass eigenstates

$$|n_\pm\rangle = \frac{1}{\sqrt{2}}(|n\rangle \pm |\bar{n}\rangle)$$

with mass eigenvalues $m_\pm = (m_n \pm \delta m) - i\lambda/2$.

So if start with pure $|n\rangle$ state at $t = 0$, then there is a finite probability P for it to be an $|\bar{n}\rangle$ at $t \neq 0$:

$$P(n(t) = \bar{n}) = |\langle\bar{n}|n(t)\rangle|^2 = [\sin^2(t/\tau_{n\bar{n}})]e^{-\lambda t}$$

where $\tau_{n\bar{n}} = 1/|\delta m|$. Current limits give $\tau_{n\bar{n}} \gtrsim 10^8$ sec, so $\tau_{n\bar{n}} >> \tau_n$.

$n - \bar{n}$ Oscillations in a Magnetic Field $\vec{B}$:

- Relevant to analysis of reactor experiments searching for $n - \bar{n}$ oscillations
- n and $\bar{n}$ interact with $\vec{B}$ via magnetic moment $\vec{\mu}_{n,\bar{n}}$, $\mu_n = -\mu_{\bar{n}} = -1.9\mu_N$, where $\mu_N = e/(2m_N) = 3.15 \times 10^{-14}$ MeV-Tesla, so

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

Diagonalization yields mass eigenstates

$$|n_1\rangle = \cos\theta \; |n\rangle + \sin\theta \; |\bar{n}\rangle \ , \qquad |n_2\rangle = -\sin\theta \; |n\rangle + \cos\theta \; |\bar{n}\rangle$$

where

$$\tan(2\theta) = -\frac{\delta m}{\vec{\mu}_n \cdot \vec{B}}$$

with eigenvalues

$$m_{1,2} = m_n \pm \sqrt{(\vec{\mu}_n \cdot \vec{B})^2 + (\delta m)^2} \; - i\lambda/2$$

Experiments reduced $|\vec{B}| = B$ to $B \sim 10^{-4}$ G $= 10^{-8}$ T, so $|\mu_n|B \simeq 10^{-21}$ MeV. Since $|\delta m| \lesssim 10^{-29}$ MeV $<< |\mu_n|B$ from exp., $|\theta| << 1$ and

$$\Delta E \equiv m_1 - m_2 = 2\sqrt{(\vec{\mu}_n \cdot \vec{B})^2 + (\delta m)^2} \simeq 2|\vec{\mu}_n \cdot \vec{B}|$$

The transition probability is

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

In a reactor $n - \bar{n}$ experiment, arrange that n's propagate a time t such that $|\vec{\mu}_n \cdot \vec{B}|t << 1$ and also $t << \tau_n$; then

$$P(n(t) = \bar{n}) \simeq (2\theta)^2 \Big(\frac{\Delta E t}{2}\Big)^2 \simeq \left(\frac{\delta m}{\vec{\mu}_n \cdot \vec{B}}\right)^2 \left(\vec{\mu}_n \cdot \vec{B}\, t\right)^2 = [(\delta m)\, t]^2 = (t/\tau_{n\bar{n}})^2$$

Then $N_{\bar{n}} = P(n(t) = \bar{n}) N_n$, where $N_n = \phi T_{run}$, with ϕ the neutron flux and T_{run} the running time. The sensitivity of the experiment depends in part on the product $t^2\phi$, so, with adequate magnetic shielding, want to maximize t, subject to the condition that $|\vec{\mu}_n \cdot \vec{B}|t << 1$.

Most sensitive reactor $n - \bar{n}$ exp. done with ILL High Flux Reactor (HFR) at Grenoble (Baldo-Ceolin, Fidecaro,.., 1985-1994), last, $L \sim 60$ m, neutrons cooled to liq. D_2 temp., kinetic energy $E \simeq 2 \times 10^{-3}$ eV, typical velocity $v \simeq 600$ m/s, $t \simeq 0.1$ sec., $\phi \sim 1.6 \times 10^{11}$ n/s; set limit

$$\tau_{n\bar{n}} \geq 0.86 \times 10^8 \text{ sec} \quad (90 \% \, CL)$$

i.e., $|\delta m| = 1/\tau_{n\bar{n}} \leq 0.77 \times 10^{-29}$ MeV.

Promising prospects for improvements of this old limit for free neutron propagation with exp. at Fermilab (talks by Kamyshkov, Snow, Gabriel, Young), taking advantage of spallation target, higher n fluxes, with requisite degaussing of propagation line. Goal of new experiment: sensitivity up to $\tau_{n\bar{n}} \sim 10^{10}$ sec.

If see positive signal, can check by reducing degaussing, thereby removing the oscillation.

To put the projected sensitivity of this future $n - \bar{n}$ search experiment in context, compare with limits on $n - \bar{n}$ oscillations from large nucleon decay detectors.

$n - \bar{n}$ Oscillations in Matter:

For $n - \bar{n}$ oscillations involving a neutron bound in a nucleus, consider

$$\mathcal{M} = \begin{pmatrix} m_{n,eff.} & \delta m \\ \delta m & m_{\bar{n},eff.} \end{pmatrix}$$

with

$$m_{n,eff} = m_n + V_n \ , \quad m_{\bar{n},eff.} = m_n + V_{\bar{n}}$$

where the nuclear potential V_n is real, $V_n = V_{nR}$, but $V_{\bar{n}}$ has an imaginary part representing the $\bar{n}N$ annihilation: $V_{\bar{n}} = V_{\bar{n}R} - iV_{\bar{n}I}$ with
$V_{nR}, \ V_{\bar{n}R}, \ V_{\bar{n}I} \sim O(100)$ MeV.
Mixing is thus strongly suppressed; $\tan(2\theta)$ is determined by

$$\frac{2\delta m}{|m_{n,eff.} - m_{\bar{n},eff.}|} = \frac{2\delta m}{\sqrt{(V_{nR} - V_{\bar{n}R})^2 + V_{\bar{n}I}^2}} << 1$$

Using the reactor exp. bound on $|\delta m|$, this gives $|\theta| \lesssim 10^{-31}$. This suppression in mixing is compensated for by the large number of nucleons in a nucleon decay detector such as Soudan-2 or SuperKamiokande e.g., $\sim 10^{33}$ n's in SuperK.

Eigenvalues:

$$m_{1,2} = \frac{1}{2}\left[m_{n,eff.} + m_{\bar{n},eff.} \pm \sqrt{(m_{n,eff.} - m_{\bar{n},eff.})^2 + 4(\delta m)^2} \right]$$

Expanding m_1 for the mostly n mass eigenstate $|n_1\rangle \simeq |n\rangle$,

$$m_1 \simeq m_n + V_n - i\frac{(\delta m)^2 \, V_{\bar{n}I}}{(V_{nR} - V_{\bar{n}R})^2 + V_{\bar{n}I}^2}$$

Imaginary part leads to matter instability via $\bar{n}n, \ \bar{n}p \to \pi$'s, with mean multiplicity $\langle n_\pi \rangle \simeq 4-5$ and rate

$$\Gamma_m = \frac{1}{\tau_m} = \frac{2(\delta m)^2 |V_{\bar{n}I}|}{(V_{nR} - V_{\bar{n}R})^2 + V_{\bar{n}I}^2}$$

So $\tau_m \propto (\delta m)^{-2} = \tau_{n\bar{n}}^2$. Writing $\tau_m = R\,\tau_{n\bar{n}}^2$, one has $R \simeq 100$ MeV, i.e.,

$$R \simeq 1 \times 10^{23} \ \mathrm{s}^{-1}$$

So lower bound on $\tau_{n\bar{n}}$ from $n - \bar{n}$ searches in reactor experiments thus yields a lower bound on τ_m and vice versa; with estimated inputs for V_{nR}, $V_{\bar{n}R}$, and $V_{\bar{n}I}$, $\tau_{n\bar{n}} > 0.86 \times 10^8$ s yields $\tau_m \gtrsim 2 \times 10^{31}$ yr.

Direct limits on matter instability have been reported by IMB, Kamiokande, Frejus, Soudan-2, SNO, and SuperK.

Signature: $\bar{n}$ annihilation in nucleus (Fe in Soudan, O in SuperK) yields multiple pions.

Soudan-2 limit: $\tau_m > 0.72 \times 10^{32}$ yr (90 % CL; Chung et al., PRD 66, 032004 (2002)). From $\tau_{n\bar{n}} = \sqrt{\tau_m/R}$, this is equivalent to $\tau_{n\bar{n}} \gtrsim 1.3 \times 10^8$ sec.

SuperK has reported a limit (Abe et al., arXiv:1009.4227): $\tau_m > 1.9 \times 10^{32}$ yr (90 % CL), equivalent to $\tau_{n\bar{n}} \gtrsim 2.4 \times 10^8$ sec (talk by Kearns).

The envisioned free neutron propagation experiment has the potential to improve substantially on these limits; achieving sensitivities of $\tau_{n\bar{n}} \sim 10^9$ s to 10^{10} s would be roughly equivalent to

$$\tau_m \simeq (3 \times 10^{33}\ \mathrm{yr}) \left(\frac{\tau_{n\bar{n}}}{10^9\ \mathrm{s}} \right)^2$$

Operator Analysis and Estimate of Matrix Elements

At the quark level $n \longrightarrow \bar{n}$ is $(udd) \longrightarrow (u^c d^c d^c)$. This is mediated by 6-quark operators $\mathcal{O}_i$, so the effective Hamiltonian is

$$\mathcal{H}_{eff} = \sum_i c_i \mathcal{O}_i$$

For d-dimensional spacetime the dimension of a fermion field ψ in mass units is $d_\psi = (d-1)/2$, so dimension $d_{\mathcal{O}_i} = 6d_\psi = 3(d-1)$ and $d_{c_i} = d - d_{\mathcal{O}_i} = 3 - 2d$. For $d = 4$, $d_\psi = 3/2$, $d_{\mathcal{O}_i} = 9$, and $d_{c_i} = -5$. If the fundamental physics yielding the $n - \bar{n}$ oscillation is characterized by a mass scale M_X, then expect $c_i \sim a_i M_X^{-5}$ so with $H_{eff} = \int d^3x \mathcal{H}_{eff}$, the transition amplitude is

$$\delta m = \langle \bar{n} | H_{eff} | n \rangle = \frac{1}{M_X^5} \sum_i a_i \langle \bar{n} | \mathcal{O}_i | n \rangle$$

Hence $\delta m \sim a \Lambda_{QCD}^6 / M_X^5$, where a is a generic a_i and $\Lambda_{QCD} \simeq 200$ MeV arises from the matrix element $\langle \bar{n} | \mathcal{O}_i | n \rangle$. $M_X \sim \text{few} \ \times 10^5 \text{ GeV} \iff \tau_{n\bar{n}} \simeq 10^9 \text{ s}.$

Operators $\mathcal{O}_i$ must be color singlets and, for M_X larger than the electroweak symmetry breaking scale, also $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$-singlets. Relevant operators:

$$\mathcal{O}_1 = [u_R^{\alpha T} C u_R^{\beta}][d_R^{\gamma T} C d_R^{\delta}][d_R^{\rho T} C d_R^{\sigma}](T_s)_{\alpha\beta\gamma\delta\rho\sigma}$$

$$\mathcal{O}_2 = [u_R^{\alpha T} C d_R^{\beta}][u_R^{\gamma T} C d_R^{\delta}][d_R^{\rho T} C d_R^{\sigma}](T_s)_{\alpha\beta\gamma\delta\rho\sigma}$$

$$\mathcal{O}_3 = [Q_L^{i\alpha T} C Q_L^{j\beta}][u_R^{\gamma T} C d_R^{\delta}][d_R^{\rho T} C d_R^{\sigma}]\epsilon_{ij}(T_a)_{\alpha\beta\gamma\delta\rho\sigma}$$

$$\mathcal{O}_4 = [Q_L^{i\alpha T} C Q_L^{j\beta}][Q_L^{k\gamma T} C Q_L^{m\delta}][d_R^{\rho T} C d_R^{\sigma}]\epsilon_{ij}\epsilon_{km}(T_a)_{\alpha\beta\gamma\delta\rho\sigma}$$

where $Q_L = \binom{u}{d}_L$, i, j.. are SU(2)$_L$ indices, and color tensors are

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

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

$(T_s)_{\alpha\beta\gamma\delta\rho\sigma}$ is symmetric in the indices $(\alpha\beta)$, $(\gamma\delta)$, $(\rho\sigma)$.

$(T_a)_{\alpha\beta\gamma\delta\rho\sigma}$ is antisymmetric in $(\alpha\beta)$ and $(\gamma\delta)$ and symmetric in $(\rho\sigma)$.

A given theory determines the coefficients c_i; then one needs to calculate the matrix elements $\langle \bar{n}|\mathcal{O}_i|n\rangle$ to predict δm and thus the resultant $n - \bar{n}$ rate.

Calculation of these matrix elements $\langle \bar{n}|\mathcal{O}_i|n\rangle$ was performed using the MIT bag model (Rao and Shrock, Phys. Lett. B 116, 239 (1982); further results varying MIT bag parameters in Rao and Shrock, Nucl. Phys. B 232, 143 (1984)).

Calculations involve integrals over sixth-power polynomials of spherical Bessel functions from the quark wavefunctions in the bag model. Results:

$$|\langle \bar{n}|\mathcal{O}_i|n\rangle| \sim O(10^{-4})\ \mathrm{GeV}^6 \simeq (200\ \mathrm{MeV})^6 \simeq \Lambda_{QCD}^6$$

It is valuable to go beyond the approximations of the MIT bag model and to calculate these matrix elements in full QCD using lattice gauge theory methods. Current effort underway (M. Buchoff, Univ. Colorado Lattice Workshop, 2012)

$n - \bar{n}$ Oscillations in an Extra-Dimensional Model

We provide a simple example of a model with $n - \bar{n}$ oscillations at an observable level (Nussinov and Shrock, Phys. Rev. Lett. 88, 171601 (2002)) in which proton decay can be strongly suppressed.

We focus on theories where SM fields can propagate in the extra dimensions and the wavefunctions of SM fermions have strong localization (with Gaussian profiles) at various points (branes) in this extra-dimensional space. Effective size of extra dimension(s) is L; $\Lambda_L = L^{-1}$ can be ~ 100 TeV, $<< M_{Pl}$.

Such models are of interest partly because they can provide a mechanism for obtaining a hierarchy in fermion masses and quark mixing. Although these are just toy models, they show how observable $n - \bar{n}$ oscillations can arise in physics beyond the SM.

In generic models of this type, excessively rapid proton decay can be avoided by arranging that the wavefunction centers of the u and d quarks are separated far from those of the e and μ. However, this does not guarantee adequate suppression of $n - \bar{n}$ oscillations. We have analyzed this.

Denote usual spacetime coords. as x_ν, $\nu = 0, 1, 2, 3$ and consider ℓ extra compact coordinates, y_λ. Let SM fermion have the form $\Psi(x, y) = \psi(x)\chi(y)$, where $\chi(y)$ has support for $0 \le y_\lambda \le L$.

Use a low-energy effective field theory approach with an ultraviolet cutoff M_* and consider only lowest relevant mode in the Kaluza-Klein (KK) mode decompositions of each Ψ field.

To get hierarchy in 4D fermion mass matrices, have the fermion wavefunctions $\chi(y)$ localized with Gaussian profiles of half-width $\mu^{-1} << L$ at various points in the higher-dimensional space:

$$\chi_f(y) = Ae^{-\mu^2|y-y_f|^2}$$

where $|y_f| = (\sum_{\lambda=1}^{\ell} y_{f,\lambda}^2)^{1/2}$.

Starting from the Lagrangian in the d-dimensional spacetime, one obtains the resultant low-energy effective field theory in 4D by integrating over the extra ℓ dimension(s). The normalization factor $A = (2/\pi)^{\ell/4}\mu^{\ell/2}$ is included so that after this integration the 4D kinetic term $\bar{\psi}(x)i\partial\!\!\!/\psi(x)$ has canonical normalization.

Denote $\xi = \mu/\Lambda_L$; choice $\xi \sim 30$ yields adequate separation of fermions while fitting in interval $[0, L]$. (Localization method for $\ell = 1$: coupling fermion to scalar field with a kink; similarly for $\ell = 2$.)

A Yukawa interaction in the d-dimensional space with coefficients of order unity and moderate separation of localized wavefunctions yields a strong hierarchy in the effective low-energy 4D Yukawa interaction because the convolution of two of the fermion Gaussian wavefunctions is another Gaussian,

$$\int d^\ell y \bar{\chi}(y_f)\chi(y_{f'}) \sim \int d^\ell y e^{-\mu^2|y-y_f|^2} e^{-\mu^2|y-y_{f'}|^2} \sim e^{-(1/2)\mu^2|y_f-y_{f'}|^2}$$

Have UV cutoff M_* satisfying $M_* > \mu$ for the validity the low-energy effective field theory analysis. Take $\Lambda_L \sim 100$ TeV for adequate suppression of neutral flavor-changing currents; with $\xi = 30$, this yields $\mu \sim 3 \times 10^3$ TeV.

In d-dimensions, $\mathcal{H}_{eff,4+\ell} = \sum_{i=1}^4 \kappa_i O_i$, where the operators O_i are comprised of the $(4+\ell)$-dimensional quark fields corresponding to those in $\mathcal{O}_i$ as Ψ corresponds to ψ. Here mass dimension of coefficients $d_{\kappa_i} = 3 - 2d = -(5+2\ell)$. Hence we write $\kappa_i = \eta_i / M_X^{5+2\ell}$ and, with no loss of generality, take $\eta_4 = 1$. Scale M_X is plausibly $\sim \Lambda_L$.

Now carry out the integrations over y to get, for each i,

$$c_i \mathcal{O}_i(x) = \kappa_i \int d^\ell y O_i(x,y)$$

Consider case $\ell = 2$. Denoting

$$\rho_c \equiv \frac{4\mu^4}{3\pi^2 M_X^9}$$

we find

$$c_i = \rho_c \eta_i \exp\left[-(4/3)\mu^2 |y_{u_R} - y_{d_R}|^2\right] \ , i = 1, 2$$

$$\begin{aligned} c_3 &= \rho_c \eta_3 \exp[-(1/6)\mu^2 (2|y_{Q_L} - y_{u_R}|^2 + 6|y_{Q_L} - y_{d_R}|^2 \\ &+ 3|y_{u_R} - y_{d_R}|^2)] \end{aligned} \tag{1}$$

$$c_4 = \rho_c \exp\left[-(4/3)\mu^2 |y_{Q_L} - y_{d_R}|^2\right]$$

Fit to data for $\ell = 2$ gives

$$|y_{Q_L} - y_{u_R}| = |y_{Q_L} - y_{d_R}| \simeq 5\mu^{-1}$$
$$|y_{u_R} - y_{d_R}| \simeq 7\mu^{-1}$$

Can also include corrections due to Coulombic gauge interactions between fermions (Nussinov and Shrock, Phys. Lett. B 526, 137 (2002)).

We find c_j for $j = 1, 2, 3$ are $<< c_4$, and hence focus on c_4.

To leading order (neglecting small CKM mixings), $|y_{Q_L} - y_{d_R}|$ is determined by m_d via relation (with $v = 246\ \mathrm{GeV} = 2m_W/g$)

$$m_d = h_d \frac{v}{\sqrt{2}}$$

with

$$h_d = h_{d,0} \exp[-(1/2)\mu^2 |y_{Q_L} - y_{d_R}|^2]$$

where $h_{d,0}$ is the Yukawa coupling in the $(4+\ell)$-dimensional space, so that

$$\exp\left[-(1/2)\mu^2 |y_{Q_L} - y_{d_R}|^2\right] = \frac{2^{1/2} m_d}{h_{d,0} v}$$

Take $h_{d,0} \sim 1$ and $m_d \simeq 10$ MeV; then contribution to δm from $\mathcal{O}_4$ term is

$$\delta m \simeq c_4 \langle \bar{n} | \mathcal{O}_4 | n \rangle \simeq \left(\frac{4\mu^4}{3\pi^2 M_X^9} \right) \left(\frac{2^{1/2} m_d}{v} \right)^{8/3} \langle \bar{n} | \mathcal{O}_4 | n \rangle$$

From MIT bag model calculation we have

$$\langle \bar{n} | \mathcal{O}_4 | n \rangle \simeq 0.9 \times 10^{-4}\ \mathrm{GeV}^6$$

Requiring that the resultant $|\delta m|$ be less than the experimental limit $\tau_{n\bar{n}} > 3 \times 10^8$ sec, i.e., $|\delta m| < 2 \times 10^{-33}$ GeV, we obtain the bound

$$M_X \gtrsim (50 \text{ TeV}) \left(\frac{\tau_{n\bar{n}}}{3 \times 10^8 \text{ sec}} \right)^{1/9} \times \left(\frac{\mu}{3 \times 10^3 \text{ TeV}} \right)^{4/9} \left(\frac{|\langle \bar{n}|O_4|n\rangle|}{0.9 \times 10^{-4} \text{ GeV}^6} \right)^{1/9}$$

Uncertainty in calculation of matrix element $\langle \bar{n}|\mathcal{O}_4|n\rangle$ is relatively unimportant for this bound because of the $1/9$ power.

Hence, for relevant values of $M_X \sim 50 - 100$ TeV, $n - \bar{n}$ oscillations might occur at levels that are in accord with the current experiment limit but not too far below this limit. Non-observation of $n - \bar{n}$ oscillations and a new limit $\tau > 10^{10}$ s would further constrain (or possibly disfavor) this type of model.

Other models with observable $n - \bar{n}$ oscillations discussed at this workshop by Babu, Mohapatra, Wise.

Conclusions

- $n - \bar{n}$ oscillations are an interesting possible manifestation of baryon number violation, of $|\Delta B| = 2$ type, complementary to proton decay. A discovery of $n - \bar{n}$ oscillations would be of profound significance.

- We have presented a model that shows how new physics beyond the SM can produce $n - \bar{n}$ oscillations at rates comparable with current limits.

- As illustrated by our model, the possibility and importance of $n - \bar{n}$ oscillations with $\tau_{n\bar{n}}$ only slightly greater than current lower limit provide a strong motivation for a new experiment to search for $n - \bar{n}$ oscillations with greater sensitivity, as part of the US Intensity Frontier Program. A new experiment could significantly improve the current limit on $n - \bar{n}$ oscillations.