Probing Possible Extra Dimensions Using $n - \bar{n}$ Oscillations

Robert Shrock
YITP, Stony Brook University

DUSEL Workshop, CCAPP, Ohio State University, April, 2008
Outline

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

• Operator analysis and estimate of matrix elements

• Calculation of $n - \bar{n}$ oscillations in a model with extra dimensions

• Oscillation analysis for $n - \bar{n}$ searches

• Main point: An extra-dimensional model provides an example of how $n - \bar{n}$ oscillations can occur at rates comparable to current limits, providing theoretical motivation for more sensitive experimental searches.
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 RS, 1982).
- Some sources of recent interest in $n - \bar{n}$ oscillations:
  - in some supersymmetric models (Babu and Mohapatra, 2001; Dutta, Mimura, Mohapatra, 2006; Babu, Mohapatra, Nasri, 2007)
  - in a model with extra dimension(s) in which SM fields propagate (Nussinov and RS, 2002) - we focus on this.
  - in models with low-scale quantum gravity (e.g., Dvali and Gabadadze, 1999; Dolgov et al., 2006, 2007)
Operator Analysis and Calculation of Matrix Elements

At the quark level $n \rightarrow \bar{n}$ is $(udd) \rightarrow (u^c d^c d^c)$. This is mediated by 6-quark operators $\mathcal{O}_i$ of the generic form $uudddd$. The effective Hamiltonian is

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

For $d$-dimensional spacetime the dimension of a fermion field $\psi$ 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 $H_{\text{eff}} = \int d^3x \mathcal{H}_{\text{eff}}$, the transition amplitude is

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

Hence $\delta m \sim a \Lambda_{QCD}^6 / M_X^5$, where $a$ is a generic $a_i$ and $\Lambda_{QCD} \sim 200$ MeV arises from the matrix element $\langle \bar{n} | \mathcal{O}_i | n \rangle$. 

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

$$O_1 = [u^\alpha_R C u^\beta_R][d^\gamma_R C d^\delta_R][d^\rho_R C d^\sigma_R](T_s)_{\alpha\beta\gamma\delta\rho\sigma}$$

$$O_2 = [u^\alpha_R C d^\beta_R][u^\gamma_R C d^\delta_R][d^\rho_R C d^\sigma_R](T_s)_{\alpha\beta\gamma\delta\rho\sigma}$$

$$O_3 = [Q^i_L C Q^j_L][u^\alpha_R C d^\beta_R][d^\gamma_R C d^\delta_R][d^\rho_R C d^\sigma_R] \epsilon_{ij} (T_a)_{\alpha\beta\gamma\delta\rho\sigma}$$

$$= 2[u^\alpha_L C d^\beta_L][u^\gamma_R C d^\delta_R][d^\rho_R C d^\sigma_R](T_a)_{\alpha\beta\gamma\delta\rho\sigma}$$

$$O_4 = [Q^i_L C Q^j_L][Q^k_L C Q^m_L][d^\rho_R C d^\sigma_R] \epsilon_{ij} \epsilon_{km} (T_a)_{\alpha\beta\gamma\delta\rho\sigma}$$

$$= 4[u^\alpha_L C d^\beta_L][u^\gamma_R C d^\delta_R][d^\rho_R C d^\sigma_R](T_a)_{\alpha\beta\gamma\delta\rho\sigma}$$

where $Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$, $i$, $j$.. are $SU(2)_L$ indices and the $SU(3)_c$ 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 \(\langle \bar{n}|O_i|n\rangle\) to predict \(\delta m\) and thus the resultant \(n - \bar{n}\) rate.

Calculation of these matrix elements \(\langle \bar{n}|O_i|n\rangle\) was performed using the MIT bag model (Rao and RS, Phys. Lett. B 116, 239 (1982)). Results involve integrals over sixth-power polynomials of spherical Bessel functions from the quark wavefunctions in the bag model. Results:

\[
|\langle \bar{n}|O_i|n\rangle| \sim O(10^{-4}) \text{ GeV}^6 \approx (200 \text{ MeV})^6 \approx \Lambda_{QCD}^6
\]

It would be worthwhile to go beyond the approximations of the MIT bag model and to calculate these matrix elements using lattice gauge theory methods. However, the bag model calculation is sufficient to give us a reasonable estimate of the expected rate of \(n - \bar{n}\) oscillations for a given theoretical model.
n — \bar{n} Oscillations in an Extra-Dimensional Model

Current exp. data fully consistent with 4D Minkowski spacetime, but useful to explore possibility of extra dimensions, both from phenomenological point of view and because main candidate theory for quantum gravity - string theory - involves higher dimensions.

Here 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 $\sim 100$ 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 (e.g., Arkani-Hamed + Schmaltz; Mirabelli + Schmaltz, 2000). Although these are just toy models, they show how $n - \bar{n}$ 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 $\mu$. However, this does not guarantee adequate suppression of $n - \bar{n}$ oscillations.
We have calculated the resultant $n - \bar{n}$ oscillation rate (Nussinov and RS, Phys. Rev. Lett. 88, 171601 (2002); see also Huber and Shafi, Phys. Lett. 512, 365 (2001)).

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

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 $\Psi$ field.

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

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

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 $\ell$ dimension(s). The normalization factor $A = (2/\pi)^{\ell/4} \mu^{\ell/2}$ is included so that after this integration the 4D kinetic term $\bar{\psi}(x)i\partial^\ell\psi(x)$ has canonical normalization.
Denote $\xi = \mu / \Lambda_L$; choice $\xi \sim 30$ yields adequate separation of fermions while fitting in interval $[0, L]$. (Fermion localization can be produced in a field-theoretic manner for $\ell = 1$ by 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 $\Lambda_L \sim O(10^2)$ 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 $O_i$ as $\Psi$ corresponds to $\psi$. Here the mass dimension of the coefficients is $d_{\kappa_i} = 3 - 2d = -(5 + 2\ell)$. Hence we write $\kappa_i = \eta_i / M_X^{5+2\ell}$ and, with no loss of generality, take $\eta_4 = 1$. The 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 the case $\ell = 2$. Denoting

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

we find

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

$$c_3 = \rho_c \eta_3 \exp \left[ -(1/6)\mu^2 (2|y_{Q_L} - y_{u_R}|^2 + 6|y_{Q_L} - y_{d_R}|^2 + 3|y_{u_R} - y_{d_R}|^2) \right]$$

$$c_4 = \rho_c \exp \left[ -(4/3)\mu^2 |y_{Q_L} - y_{d_R}|^2 \right]$$
Use fit to data for $\ell = 2$ (Arkani-Hamed and Schmaltz), which 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 RS, Phys. Lett. B 526, 137 (2002)).

We find $c_j$ for $j = 1, 2, 3$ are $\ll c_4$, 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

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

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 $\delta m$ from $\mathcal{O}_4$ term is

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

From our MIT bag model calculation we have

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

Current experimental upper limit on $|\delta m| = 1/\tau_{n\bar{n}}$ is $|\delta m| < 2 \times 10^{-33}$ GeV, i.e., $\tau_{n\bar{n}} > 3 \times 10^8$ sec. Requiring that the $|\delta m|$ from our model be less than this experimental limit, we obtain the bound

$$M_X \gtrsim (50 \text{ TeV}) \left( \frac{\tau_{n\bar{n}}}{3 \times 10^8 \text{ sec}} \right)^{1/9} \times \left( \frac{\mu}{3 \times 10^3 \text{ TeV}} \right)^{4/9} \left( \frac{|\langle \bar{n} | \mathcal{O}_4 | n \rangle|}{0.9 \times 10^{-4} \text{ GeV}^6} \right)^{1/9}$$

The 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, this model predicts that $n - \bar{n}$ oscillations could occur at levels that are in accord with the current experiment limit but not too far below this limit. The model thus provides motivation for higher-sensitivity experimental searches for $n - \bar{n}$ oscillations. We comment on the status of these searches next.
Oscillation analysis for $n - \bar{n}$ searches

$n - \bar{n}$ Oscillations in Field-Free Vacuum: We have $\langle n | H_{eff} | n \rangle = m_n - i\lambda/2$ and (assuming CPT), $\langle \bar{n} | H_{eff} | \bar{n} \rangle = m_n - i\lambda/2$, where $H_{eff}$ denotes relevant Hamiltonian and $\lambda^{-1} = \tau_n = 0.89 \times 10^3$ sec. $H_{eff}$ may also mediate $n \leftrightarrow \bar{n}$ transitions: $\langle \bar{n} | H_{eff} | n \rangle \equiv \delta m$. Consider the $2 \times 2$ 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 limit: $\tau_{n\bar{n}} \gtrsim 10^8$ 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 $\mu_{n,\bar{n}}$, $\mu_n = -\mu_{\bar{n}} = -1.9\mu_N$, where $\mu_N = e/(2m_N) = 3.15 \times 10^{-14}$ MeV-Tesla, so

  \[ M = \begin{pmatrix} m_n - \mu_n \cdot \vec{B} - i\lambda/2 & \delta m \\ \delta m & m_n + \mu_n \cdot \vec{B} - i\lambda/2 \end{pmatrix} \]

Diagonalization yields mass eigenstates

\[ |n_1\rangle = \cos \theta |n\rangle + \sin \theta |\bar{n}\rangle, \quad |n_2\rangle = -\sin \theta |n\rangle + \cos \theta |\bar{n}\rangle \]

where

\[ \tan(2\theta) = -\frac{\delta m}{\mu_n \cdot \vec{B}} \]

with eigenvalues

\[ m_{1,2} = m_n \pm \sqrt{(\mu_n \cdot \vec{B})^2 + (\delta m)^2 - i\lambda/2} \]
Experimentally, reduce $|\mathbf{B}| = B$ to $B \sim 10^{-4}$ G $= 10^{-8}$ T, so $|\mu_n|B \sim 10^{-21}$ MeV. Since $|\delta m| << |\mu_n|B$ from exp., $|\theta| << 1$ and

$$\Delta E \equiv m_1 - m_2 = 2\sqrt{(\mu_n \cdot \mathbf{B})^2 + (\delta m)^2} \simeq 2|\mu_n \cdot \mathbf{B}|.$$ 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 $|\mu_n \cdot \mathbf{B}|t << 1$ (and thus also $t << \tau_n$); then

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

Then $N_{\bar{n}} = P(n(t) = \bar{n})N_n$, where $N_n = \phi T_{run}$, with $\phi$ 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 $|\mu_n \cdot \mathbf{B}|t << 1$. 
Most sensitive reactor $n - \bar{n}$ exps. done with ILL High Flux Reactor (HFR) at Grenoble (Baldo-Ceolin, Fidecaro,.., 1985-1994), last, $L \sim 70$ m, neutrons cooled to liq. D$_2$ temp., kinetic energy $E \sim 2 \times 10^{-3}$ eV, vel. $v \sim 600$ m/s, $t \sim 0.11$ sec., $\phi \sim 1.25 \times 10^{11}$ n/s, set limit

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

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

Many years since this last reactor experiment; ideas for new reactor exps. (Kamyshkov et al.), in particular, an experiment with a MW-class reactor, cryogenic apparatus to slow the $n$’s down, combined with a long vertical, magnetically shielded tube for $n$’s to propagate down to a deep underground detector at DUSEL (see talk by Kamyshkov).

To put the sensitivity of a reactor $n - \bar{n}$ 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 $V_{nR}, V_{\bar{n}R}, V_{\bar{n}I} \sim O(100) \text{ MeV}$.

Mixing is thus suppressed; $\tan(2\theta)$ is determined by

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

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:

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

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 annihilation processes \( \bar{n}n, \bar{n}p \rightarrow \pi \)'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 \( \tau_m \propto \tau_{n\bar{n}}^2 \). Write \( \tau_m = R \tau_{n\bar{n}}^2 \), where \( R \) depends on \( V_{nR}, V_{\bar{n}R}, V_{\bar{n}I} \) for a given nucleus. Lower bound on \( \tau_{n\bar{n}} \) from \( n - \bar{n} \) searches in a reactor experiment thus yields a lower bound on \( \tau_m \) for a given nucleus and vice versa.
\[
\left( \frac{\tau_m}{10^{31} \text{ yr}} \right) \simeq 1.6 \left( \frac{R}{0.5 \times 10^{23} \text{ s}^{-1}} \right) \left( \frac{\tau_{n\bar{n}}}{10^8 \text{ s}} \right)^2
\]

\[R^{16}\text{O}) \simeq 0.5 \times 10^{23} \text{ s}^{-1}, \ R^{56}\text{Fe}) \simeq 0.7 \times 10^{23} \text{ s}^{-1} \ (\text{Dover, Gal, Richard 1983,... Gal 2008})\]

So the reactor exp. limit \( \tau_{n\bar{n}} > 0.86 \times 10^8 \text{ sec.} \) yields \( \tau_m \gtrsim 10^{31} \text{ yr} \) for matter exp.

Signatures of \( n - \bar{n} \) in matter are not as direct as, e.g., \( p \rightarrow e^+\pi^0 \), and data analysis is more complicated due to interaction of \( \pi^\pm \)'s in nucleus. Direct limits on matter instability have been reported by IMB, Kamiokande, Frejus, Soudan-2, and SuperK, in particular,

Soudan-2 limit: \( \tau_m > 0.72 \times 10^{32} \text{ yr} \) (90 % CL; Chung et al., 2002) for \( n \)'s in iron, equiv. to \( \tau_{n\bar{n}} \gtrsim 2 \times 10^8 \text{ sec.} \)

preliminary SuperK limit: \( \tau_m > 1.8 \times 10^{32} \text{ yr} \) (90 % CL; Ganezer, LBL Conf. on Searches for \( B \) and \( L \) Violation, 2007) for \( n \)'s in oxygen, equiv. to \( \tau_{n\bar{n}} \gtrsim 3 \times 10^8 \text{ sec.} \)
SNO (Sudbury Neutrino Observatory) expects to obtain a limit also. The smaller mass of the SNO detector is partially compensated by the property that the nuclear potential felt by the $n$ in the deuteron is smaller than in iron or oxygen.

Since $\tau_m \propto \tau_{n\bar{n}}^2$, a factor of 30 improvement in the lower bound on $\tau_{n\bar{n}}$ from a direct search experiment for $n - \bar{n}$ oscillations is equivalent to a factor of $\sim 10^3$ improvement in an experiment searching for matter instability due to $n - \bar{n}$ oscillations. Hence direct search experiment can achieve greater reach, set better limit or perhaps make a discovery.
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.

• Our calculation in an extra-dimensional model provides an example of how new physics beyond the standard model can produce $n - \bar{n}$ oscillations at rates comparable with current experimental limits. Similar results are obtained in other extra-dimensional models. Together with the 4D supersymmetric models of Mohapatra et al., this provides motivation for new experimental searches for $n - \bar{n}$ oscillations.

• Existing limits on $n - \bar{n}$ oscillations have been obtained by reactor experiments and deep underground nucleon decay detectors. A new reactor experiment at DUSEL could achieve a substantial increase in sensitivity and could set a much more restrictive limit or discover a signal.