Neutron Antineutron oscillation as a probe of Unification

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Where do we stand in our search for unification of matter and forces?

☞ **Beyond the standard model**

➢ Supersymmetry because of
(i) gauge hierarchy problem;
(ii) Radiative EWSB;
(iii) Dark matter if R-parity is conserved.
(iv) If no new physics until 10^{16} GeV, couplings unify leading to GUT theories;
(v) Provide a simple framework for addressing other cosmological issues such as inflation, baryogenesis etc.

➢ Extra dimension models : solve the gauge hierarchy problem but otherwise not at the same level of viability and versatility as SUSY models e.g. cosmology much more complicated.

Two classes of SUSY models

☞ **(i) Most explored models: MSSM, NMSSM etc which are embeddable in simple SU(5) or SO(10) GUT:**
Generally need the additional assumption of R-parity for dark matter.

(ii) An alternative class of extension of MSSM is one that explains (a) m_ν using seesaw; (b) automatic R-parity for stable dark matter but (c) not embeddable into conventinal GUTs.

Testing this possibility via a search for baryon non-conservation is the subject of this talk.

Probing unification via $\Delta B \neq 0$ is an old subject

☞ **Why $\Delta B \neq 0$?**

➢ : (i) Origin of matter requires it.

➢ (ii) Standard model has $\Delta B \neq 0$ and $\Delta L \neq 0$ but $\Delta(B-L) = 0$ due to nonperturbative effects.

➢ (iii) Most interesting physics scenarios beyond the standard model e.g. GUTs lead to $\Delta B \neq 0$.

Two distinct baryon violation signals:

☞ **Proton decay vrs $N - \bar{N}$ oscillation:**

☞ **Proton decay:**

➢ $B - L = 0$: Operator: $QQQL/M^2$;
processes: $p \to \pi^0 e^+$; $K^+ \bar{\nu}, ...$ (more later)

➢ $\tau_{p \to e^+ \pi^0} \geq 6 \times 10^{33}$ yrs. implying $M \geq 10^{15}$ GeV or so.

➢ $\Delta(B - L) = 0$ baryon nonconservation probes very high scales e.g. grand unification.

$N - \bar{N}$ oscillation

☞ **Operator responsible**

➢ $QQQQQQ/M^5,\ u^c d^c d^c u^c d^c d^c/M^5$;

➢ Note the scaling law with respect to new physics scale M;

➢ Probes new physics around 100 TeV; if $M_{eff} \gg 100$ TeV, $N - \bar{N}$ unobservable.

➢ Observation of $N - \bar{N}$ will signal a completely new direction for unification !!

➢ Present limit on osc. time $\tau_{N-\bar{N}} \geq 10^8$ sec. ILL expt. (1994); also comparable limits from baryon nonconservation searches.

Phenomenology of $N - \bar{N}$

☞

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix} N \\ \bar{N} \end{pmatrix} = \begin{pmatrix} E_n & \delta m \\ \delta m & E_{\bar{n}} \end{pmatrix} \begin{pmatrix} N \\ \bar{N} \end{pmatrix} \tag{1}$$

$P_{N\to\bar{N}} \sim \left(\frac{\delta m}{\Delta E_n}\right)^2 sin^2 \Delta E_n t$

☞ **Two cases**

➢ Case (i): $\Delta E_n t \ll 1$

$P_{N\to\bar{N}} \sim (\delta m \cdot t)^2 \equiv \left(\frac{t}{\tau_{N-\bar{N}}}\right)^2$
corresponds to free neutron oscillation;

➢ Case (i): $\Delta E_n \cdot t \gg 1$

$P_{N\to\bar{N}} \sim \left(\frac{\delta m}{2\Delta E_n}\right)^2$
corresponds to bound neutrons.

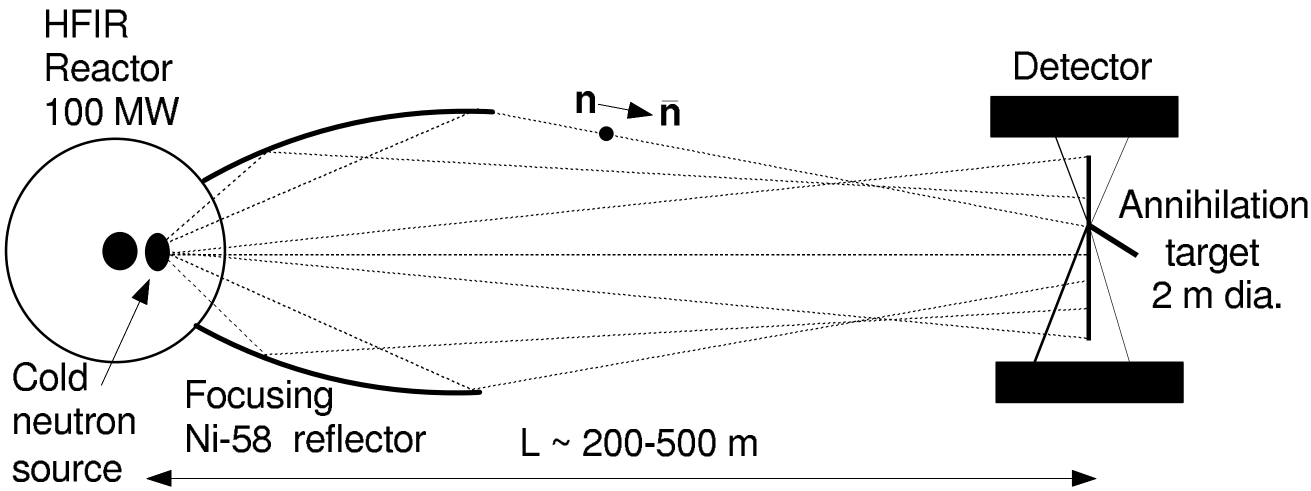
Curious coincidence

☞ **Stability of Nuclei to $\Delta B \neq 0$ should give a limit on $\tau_{N-\bar{N}}$:**

To see what this is, note that for nuclei,
$E_N - E_{\bar{N}} \sim 100$ **MeV; so**

$\tau_{Nucl.} \sim \left(\frac{\delta m}{2\Delta E_n}\right)^{-2} 10^{-23}$ **sec. This should be** $\geq 10^{32}$ **yrs.**
$\rightarrow \delta m \leq 10^{-29}$ **MeV or** $\tau_{N-\bar{N}} \geq 10^{8}$ **sec.**

We will see that present reactor neutron fluxes are precisely in the right range to probe these values of $\tau_{N-\bar{N}}$.



Reactor Search Expt. set-up: ILL (1994)

☞

☞ **Key Formula for doing an expt.**

# of events = $N\left(\frac{t}{\tau_{N-\bar{N}}}\right)^2 \times T \sim 1$
where N **= reactor flux;** $v_N t$**= distance to detector;**
T **running time.**

Feasibility of the expt

☞ **Maximum reactor fluxes for (100 MW)**$\sim 10^{13} - 10^{14}$ **N/cm**^{2} **sec.; for** $t = 0.1$ **sec. and** $T \sim 3$ **years can yield a limit of** 10^{10} **sec.**

Need to ensure that there is a magnetic shielding to the level of 10^{-4} **Gauss which is achieved by** μ**-meta shielding.**

Present limit from ILL, 1994: $\tau_{N-\bar{N}} \geq 8.6 \times 10^7$ **sec.**

New search effort and proposal by Y. Kamyshkov, hep-ex/0211006 but no concrete site yet (nor funding).

Can we learn about $\Delta(B-L)=2$ processes from Nucleon decay searches ?

☞ **Approximate relation between $\tau_{N-\bar{N}}$ and non-leptonic Nucleon decay lifetime:**

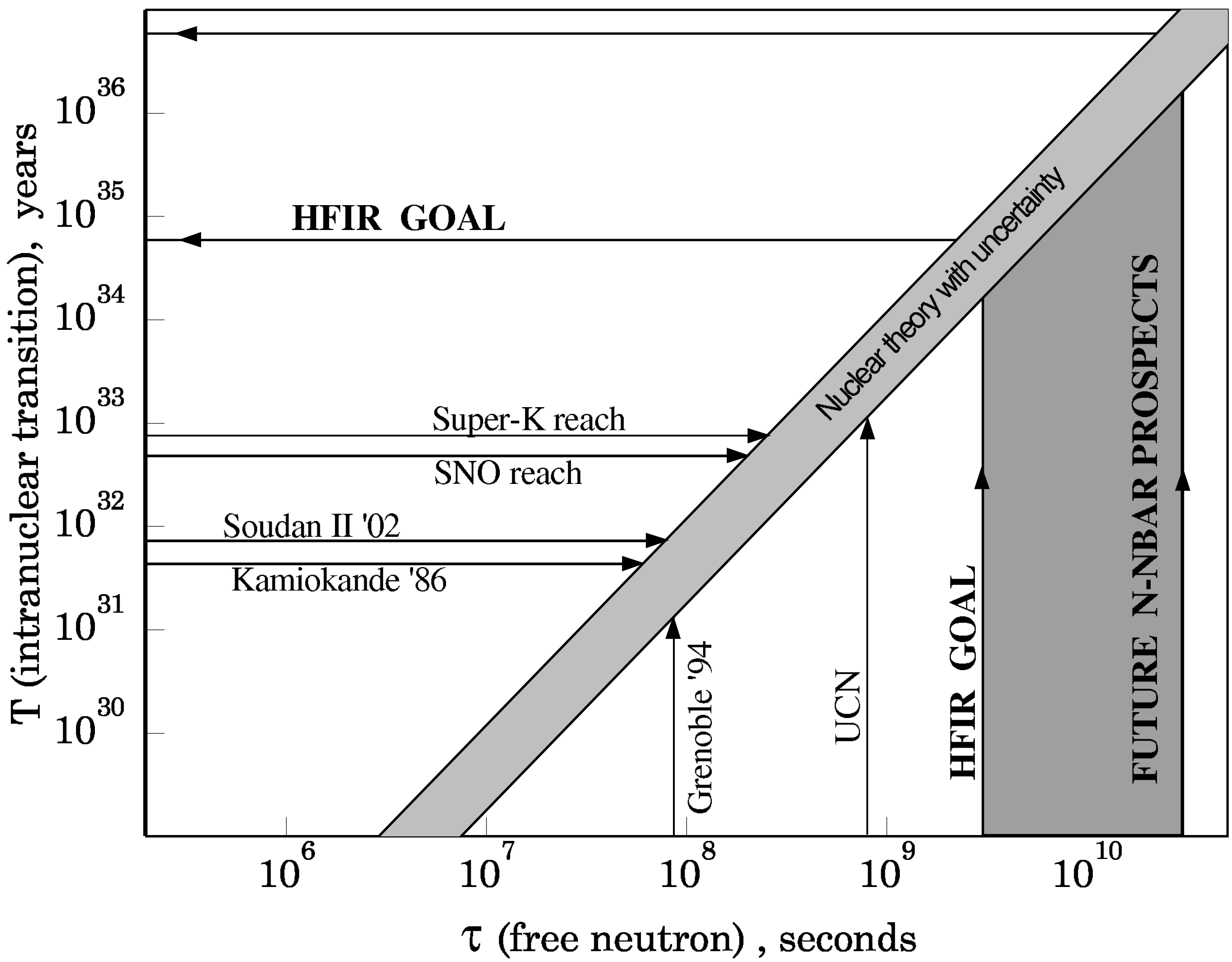
$$\tau^{-1}_{N-decay} \approx f\left(\frac{1}{\tau_{N-\bar{N}} V_N}\right)^2 10^{+23}\ sec^{-1}$$

$$\boxed{\tau_{N-\bar{N}} \sim 10^8 \text{ sec.} \leftrightarrow \tau_{N-decay} \sim f^{-1} 10^{32} \text{ yrs.}}$$

f, the nuclear fudge factor is hard to calculate reliably; $N-\bar{N}$ process clean !!

For attempts see Dover, Gal, Richards; Alberico et al.;

☞

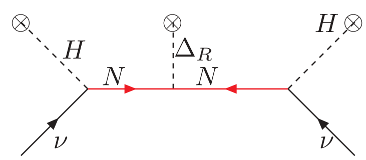


T (intranuclear transition), years
10^36
10^35
10^34
10^33
10^32
10^31
10^30
HFIR GOAL
Super-K reach
SNO reach
Soudan II '02
Kamiokande '86
Nuclear theory with uncertainty
Grenoble '94
UCN
HFIR GOAL
FUTURE N-NBAR PROSPECTS
10^6
10^7
10^8
10^9
10^10
τ (free neutron) , seconds

How theoretically compelling is $N - \bar{N}$?

☞ $m_\nu \neq 0 \leftrightarrow N - \bar{N}$ connection

- ➢ $m_\nu \neq 0$ is the first indication of new physics.
- ➢ A compelling scenario: neutrino is Majorana fermion, its small mass explained by the seesaw mechanism:



☞ $\mathcal{M}_\nu \simeq -\frac{h_\nu^2 v^2}{M_R}$; $\rightarrow m_{\nu_i} \ll m_{u,d,e...}$.

Implications of Seesaw

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- Seesaw breaks $B - L$ and
  $\Delta(B-L) = 2$
- $m_\nu \neq 0$ is $\Delta L = 2$; so is there a $\Delta B = 2$ or $N - \bar{N}$;
- Typical range of seesaw scales $M_{seesaw} \sim 10^{11} - 10^{15}$ GeV, to fit atmospheric data ($m_{\nu_3} \sim 0.05$ eV) for $m_{D,33} \sim m_\tau - m_t$.
- It could be that $M_{seesaw} \sim 10^{15}\ GeV \sim M_U$: (as in SO(10))
  $N - \bar{N}$ oscillation is unobservable!!
- Another possibility: $M_{seesaw} \sim 10^{11}$ GeV.
- Main point of the talk is that even though it may appear that $N - \bar{N}$ is unobservable in this case too, there are quite interesting theories where answer is different .

$m_\nu \neq 0 \leftrightarrow N - \bar{N}$ connection

☞ **What is a natural theory of seesaw ?**

☞ **Std model group** $SU(2)_L \times U(1)_Y \; + N_R$
$Tr(B-L)^3 \; = \; 0$ **and weak gauge group expands:**

☞ $$\boxed{SU(2)_L \times U(1)_Y \longrightarrow SU(2)_L \times SU(2)_R \times U(1)_{B-L}}$$

☞ **with** $\begin{pmatrix} u_L \\ d_L \end{pmatrix}$; $\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \oplus \begin{pmatrix} u_R \\ d_R \end{pmatrix}$; $\begin{pmatrix} N_R \\ e_R \end{pmatrix}$

$$Q \;=\; I_{3L} + I_{3R} + \frac{B-L}{2}$$

$$\Delta(B-L) \;=\; -2\Delta I_{3R} \;=\; -2$$

leads to $\nu \;=\; \bar{\nu}$ **and** $N - \bar{N}$.

$N-\bar{N}$ oscillation in left-right models with Pati-Salam Quark Lepton Unification

☞ $SU(2)_L \times SU(2)_R \times SU(4)_c$

$$F_{L,R} \equiv \begin{pmatrix} u & u & u & \nu \\ d & d & d & e \end{pmatrix}_{L,R}.$$

The Non-SUSY version with $N-\bar{N}$:

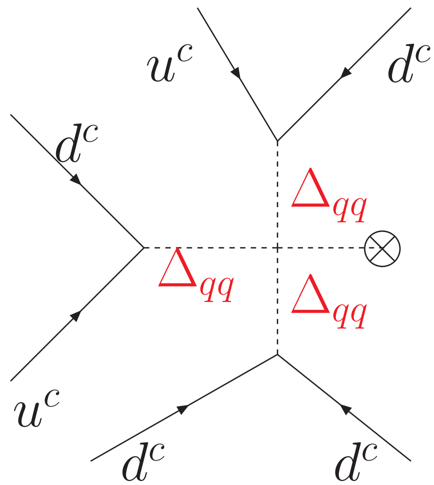
Higgs fields $\phi(2,2,1) \oplus \Phi(2,2,15)$ **and** $\Delta^c(1,3,10)$

Key to $N-\bar{N}$ is the coupling $\Delta^c F^c F^c$ which hich has in it Δ_{qq} fields which couple to two quarks.

$< \Delta^c_{\nu^c\nu^c} \neq 0 >$ **breaks B-L by 2 units.**

Diagram for $N - \bar{N}$

☞ $N - \bar{N}$ **operators** $QQQQQQ/M^5,\ u^c d^c d^c u^c d^c d^c/M^5$**:** $M = ?$



R.N.M. and Marshak (1980)

☞ $\tau_{N-\bar{N}} \propto M^5_{\Delta_{qq}}$; **Measurable for** $M_{\Delta_{qq}} = 100$ **TeV**

Two problems with the simple model

☞ **(i) Naturalness in Non-SUSY theories says that $M_{\Delta_{qq}} \sim M_{seesaw}$. So when $M_{seesaw} \sim 10^{11}$ GeV, $\tau_{N-\bar{N}}$ becomes unobservable e.g. $\tau_{N-\bar{N}} \sim 10^{38}$ sec.**

(ii) In this theory, $\Delta B = 2$ interaction are in equilibrium till about 10 TeV and therefore erase any baryons produced at higher temperatures.

Decoupling temperature: $\frac{T^{11}}{M^{10}} \leq \sqrt{g_*}\frac{T^2}{M_P}$ leads to $T_d \simeq 1$ TeV

☞ **New Result: Making model supersymmetric overcomes both problems.**

SUSY $SU(2)_L \times SU(2)_R \times SU(4)_c$ model

☞ Two new things happen

- ➢ An accidental global symmetry appears in the theory that keeps the diquark $\Delta_{u^c u^c}$ at the weak scale; Chacko, R.N.M. (1998)
- ➢ Supersymmetry introduces a new operator that has lower dimension than the nonsusy case.

  Dutta, Mimura and RNM, (2005)
- ➢ The combination of these two effects reduce the dependence on M_{seesaw} making $N - \bar{N}$ observable even for high seesaw scale.

Two cases

☞ **Case (i): All** $M_{\Delta_{qq}} \sim 10 - 100 TeV \ll M_{seesaw}$**:**

same estimate for $G_{\Delta B=2}$ **as before despite high scale seesaw.**

Case(ii) $M_{\Delta_{u^c u^c}} \sim v_{wk}$ **and others of order** M_{seesaw}**:**

$G_{\Delta B=2} \sim \frac{f^3}{M^2_{seesaw} v^3_{wk}}$ **(rather than** $G_{\Delta B=2} \sim \frac{f^3}{M^5_{seesaw}}$**)**

Details for case(i)

☞ $SU(2)_L \times SU(2)_R \times SU(4)_c$ **theory with minimal Higgs:** $\phi_i(2,2,0); \Phi(2,2,15); \Delta^c(1,3,10) \oplus \bar{\Delta}^c(1,3,\bar{10})$

Accidental symmetry of the superpotential is $U(30,c)$

Its breaking leads to light 36 diquarks Δ_{qq} **plus 12** Δ_{ql} **states and one pair of doubly charged states at the multi-TeV scale (10-100 TeV) scale.**

Proof: Break B-L by $< \Delta^c(1,3,10)_{\nu^c\nu^c} > \neq 0$ **breaks**

$U(30,c)$ **down to** $U(29,C) \rightarrow$ **59 massless states whereas** $SU(2)_L \times SU(2)_R \times SU(4)_c$ **to** $SU(2)_L \times U(1)_Y \times SU(3)_c$ **absorbs 9 of them leaving the 50 states above.**

Baryogenesis

: Babu, Nasri and RNM, 2005

☞ **Arises from the decay of a 100 GeV scalar particle S in the theory:**

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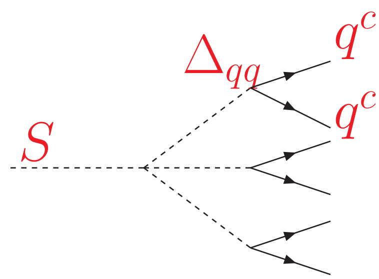

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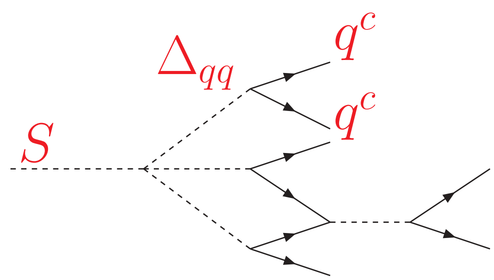


Details: Case (ii)

☞ $SU(2)_L \times SU(2)_R \times SU(4)_c$ **theory with minimal Higgs:** $\phi_i(2,2,0); \Phi(2,2,15); \Delta^c(1,3,10) \oplus \bar{\Delta}^c(1,3,\bar{10})$, $\Omega(1,3,1)$

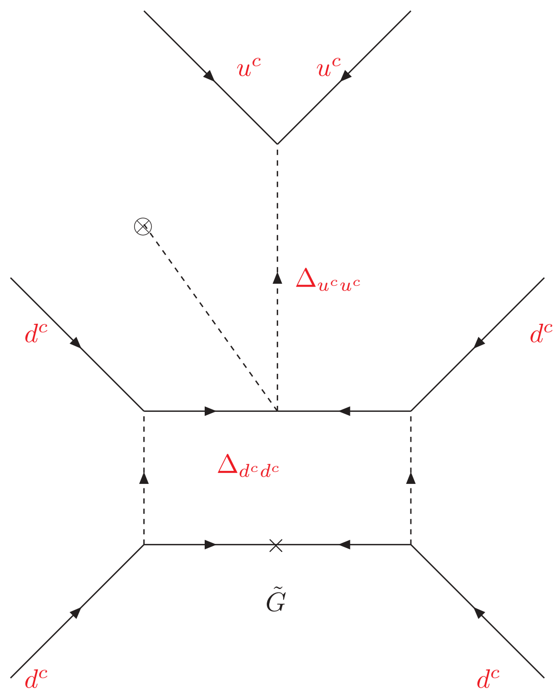
Accidental symmetry of the superpotential is $U(10,c) \times SU(2,c)$

Its breaking leads to light 12 diquarks Δ_{qq} **at the multi-TeV scale;**

Proof: Break B-L by $< \Delta^c(1,3,10)_{\nu^c\nu^c} > \neq 0$ **breaks**

$U(10,c) \times SU(2,c)$ **down to** $U(9,C) \times U(1,C) \rightarrow$ **21 massless states**
whereas $SU(2)_L \times SU(2)_R \times SU(4)_c$ **to** $SU(2)_L \times U(1)_Y \times SU(3)_c$ **absorbs 9 of them leaving the 12 states above.**

New Feynman Diagram:



☞ **which leads to** $G_{N-\bar{N}} \simeq \frac{f_{11}^3}{\lambda^2 M_{seesaw}^2 v_{wk}^3}$

For $M_{seesaw} \sim 10^{11}$ **GeV,** $f \sim 0.1$ **and** $\lambda = 0.1$**,**
$\tau_{N-\bar{N}} \sim 10^{10}$ **sec.**

☞ Origin matter and $N - \bar{N}$ oscillation: Case(ii)

➢ Does leptogenesis mechanism work
since any baryons created as long as $N - \bar{N}$ osc is in equilibrium will be erased;

➢ Because of the enhancement mechanism i.e. $\Delta_{u^c u^c}$ mass is near or below a TeV, the decoupling temperature is determined by the inequality

➢ $\frac{f^6 T^5}{M^4_{seesaw}} \leq \sqrt{g_*}\frac{T^2}{M_P}$

➢ gives decoupling temp. around 10^7 GeV: One can have resonant leptogenesis with a quasi-degenerate pair of right handed neutrinos with mass below 10^7 GeV.

Proton decay vrs $N - \bar{N}$ oscillation

☞

$N - \bar{N}$	P-decay
Probes $M_{seesaw} \sim 10^{11}$ GeV	$M_{U-seesaw} \sim 10^{16}$ GeV
$\tau_{N-\bar{N}} \sim 10^{10}$ sec.probes matter stability to 10^{37} yrs.	Only upto few$\times 10^{34}$ yrs feasible
Partial Q-L Unification	Full Unification
No P-decay	No $N - \bar{N}$
Collider signals Δ_{qq}	None Beyond MSSM

Signals at LHC

☞ **Three and Four jet production due to diquarks;**

$q\bar{q} \longrightarrow \Delta_{qq}\bar{\Delta}_{qq}$;
$\Delta_{qq} \longrightarrow qq$ - **4 jets;**

☞ $q + G \longrightarrow \bar{q}\Delta_{qq}$;
leads to 3 jet signals.
Δ_{qq} **masses upto several TeV's can be probed at LHC.**

$N - \bar{N}$ Summary

☞ $N - \bar{N}$ **osc. can answer fundamental questions e.g.**

(i) How Stable is matter ?
(ii) Where does matter come from ?
(iii) Nature of unified theories at short distances e.g. seesaw models, Non-GUT vrs GUT type theories etc.

☞

➢ With the discovery of neutrino mass, the case for $N - \bar{N}$ is now a lot stronger than it was in 1980's, specially, if $\nu = \bar{\nu}$ as many believe. It is possible to construct fully viable theories which give stable dark matter, are supersymmetric, can explain the origin of matter where $N - \bar{N}$ oscillation is observable.

☞

- ➢ Time to do a higher precision search for $N - \bar{N}$.
- ➢ Should the fact that $N - \bar{N}$ is model dependent be a negative ?

Interesting processes e.g. $\beta\beta_{0\nu}$ decay or p decay are as model dependent as $\tau_{N-\bar{N}}$. e.g.$< m >_{\beta\beta} \sim 0 - 3$ meV; (NH); $\tau_p \geq 10^{36} - 10^{34}$ yrs in SUSY GUTs .

$N - N'$ oscillation: Another similar process

☞ **What is an N' ?**

➢ String theories suggest a mirror sector to our universe;

➢ LSND if confirmed by MiniBooNe, would require sterile neutrinos which could be neutrinos from the mirror sector.

➢

visible sector $SU(3)_c \times SU(2)_L \times U(1)_Y$	mirror sector $SU(3)_c \times SU(2)_L \times U(1)_Y$
W, Z, γ, gluons $\begin{pmatrix} u_L \\ d_L \end{pmatrix}$ u_R, d_R $\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ e_R, N	W, Z, γ, gluons $\begin{pmatrix} u_L \\ d_L \end{pmatrix}$ u_R, d_R $\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ e_R, N

$N - N'$ oscillation

☞ **Every particle we are familiar with has a mirror partner with same mass in the symmetric mirror model:**
$N' \equiv u'd'd'$ **is the mirror partner of** $N \equiv udd$**.**

☞ **If there is an interaction of the form:**
$u^c d^c d^c u'^c d'^c d'^c / M^5$**, then** N **can oscillate to** N'**.**

$N - N'$ unconstrained by present data

☞ **(i) N' has only gravitational int. with known particles; as a result $N - \bar{N}$ constraints do not apply to it.**
(ii) Inside a nucleus, $N - N'$ osc. cannot take place due to energy conservation. Hence $N \rightarrow 3\nu$ constraints do not apply to it either.

☞ **$\tau_{N-N'}$ can easily be of order 1 sec.**

Bento, Berezhiani; RNM, Nasri and Nussinov (2005)

Some consequences

☞

➢ With 1 sec. osc. time, the reactor neutrons observed at large distances should lose approximately half their flux.

➢ During solar flare, energetic neutrons could penetrate the Earth and emerge on the other side. They travel inside the Earth as N' and hence unaffected.

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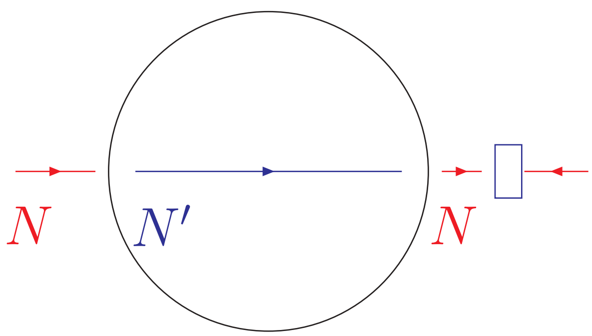

$N - N'$

☞

- Simple theories for this require that there be a light (10-1000 GeV) color triplet scalar in the theory. This can be tested at LHC. Will look like a squark but decaying to two jets.
- Int. needed is $Nu^c d^c d^c / M_1^2$ with $M_N \sim 10^{11} - 10^{12}$ GeV for seesaw neutrino mass. This implies that $M_1 \sim$ TeV to give $\tau_{NN'} \sim 1$ sec.
- Another class of interactions: $Xu^c d^{c'}, Yd^c d^{c'}$.
  Again these particles have masses around a TeV. Striking signature in colliders:

  $PP \rightarrow X\bar{X}$ with $X \rightarrow jet + missingE$.
- An amusing new possibility with ground breaking implications such as new dark matter candidate, sterile neutrinos, etc etc. Many interesting applications !!
  Will be very important to push the oscillation time higher.