PROBING B-L UNIFICATION via N-N-bar Oscillation, Proton and Rare Lepton Decays

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Plan of the Talk

1. Why B-L symmetry ?

2. Two classes of local B-L models

4. Proton Decay, Rare Lepton decays and N-N-bar Oscillations as tests of these models.

Why B-L Symmetry ?

- Standard model has global B-L symmetry.
- What is the nature of this symmetry ? Is it a global or local symmetry ?
- Is it broken or exact ? If broken, what is the breaking scale and what new physics is associated with it ?

Any Hint of B-L symmetry beyond SM?

- Neutrino Mass points towards a B-L symmetry beyond the standard model.
- As does SUSY dark matter.
- One popular way to understand the origin of matter also involves B-L breaking.

Neutrino mass and ν-standard model

- **Starting point: add RH neutrino to SM for nu mass:**

$$Q = \begin{pmatrix} u_1 & u_2 & u_3 \\ d_1 & d_2 & d_3 \end{pmatrix} \sim (3, 2, \frac{1}{6})$$

$$u^c = \begin{pmatrix} u_1^c & u_2^c & u_3^c \end{pmatrix} \sim (\bar{3}, 1, \frac{-2}{3})$$

$$d^c = \begin{pmatrix} d_1^c & d_2^c & d_3^c \end{pmatrix} \sim (\bar{3}, 1, \frac{1}{3})$$

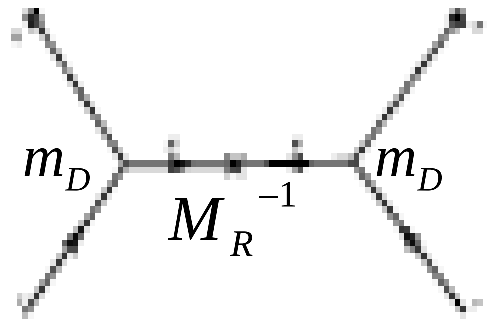
$$L = \begin{pmatrix} \nu \\ e^- \end{pmatrix} \sim (1, 2, \frac{-1}{2})$$

$$e^c \sim (1, 1, +1)$$

$$\nu^c \sim (1, 1, 0)$$

Seesaw paradigm for neutrino masses

Add right handed neutrinos to the standard model and give them a large Majorana mass:



$$m_\nu \cong -m_D^T M_R^{-1} m_D \quad << m_{u,d,e}$$

Minkowski (77), Yanagida; Gell-Mann, Ramond, Slansky; Glashow; RNM, Senjanovic (79)

Seesaw scale and B-L symmetry

- **Seesaw formula applied to atmospheric neutrino data tells us that**

$$M_R << M_{Pl}$$

- **Simple way to understand this inequality is to have a new symmetry that protects M_R. B-L is the appropriate symmetry since Majorana mass of RH neutrino breaks B-L by 2 units.**

Another reason to suspect a B-L sym.

- Common belief: SUSY at TeV scale for various reasons:

(i) Gauge hierarchy

(ii) EWSB: origin of W, Z mass

(iii) Dark matter: requires R-parity exact.

$$R = (-1)^{3(B-L)+2S}$$

Note that if B-L is a good symmetry beyond MSSM and breaks by two units (as in the RH neutrino mass), R-parity is exact in MSSM,

dark matter is stable: otherwise not !!

(RNM,86;Martin,92)

Origin of matter and B-L

- **If matter-anti-matter symmetry originated from early universe above the TeV scale, then, it must break B-L. If it did not, Sphalerons would erase it !!**

- **Proof:** **Suppose** ΔB **generated in the early Universe is such that it has B- L=0;**

Then ΔB **=** $\Delta(B+L)$ **; But B+L is violated by sphalerons which are in equilibrium down to the electroweak phase transition temp and will therefore wipe out B+L and hence all baryon asymmetry.**

B-L: Local or Global ?

- **SM or MSSM:** $$\partial_\mu J_{B-L}{}^{\mu} = 0$$
- **But** $$Tr(B-L)^3 \neq 0$$
- **So B-L is not a local symmetry.**
- **Add the RH neutrino:** $$Tr(B-L)^3 = 0$$
- **(B-L) becomes a gauge-able symmetry.**
- **We will consider B-L to be a local symmetry.**

Nu-mass, Dark Matter and N-N-bar connection

(i) Seesaw breaks B-L by two units due to the Majorana mass of the RH neutrinos.

(ii) stable dark matter as another hint of B-L with B-L=2 since $R=(-1)^{3(B-L)+2S}$

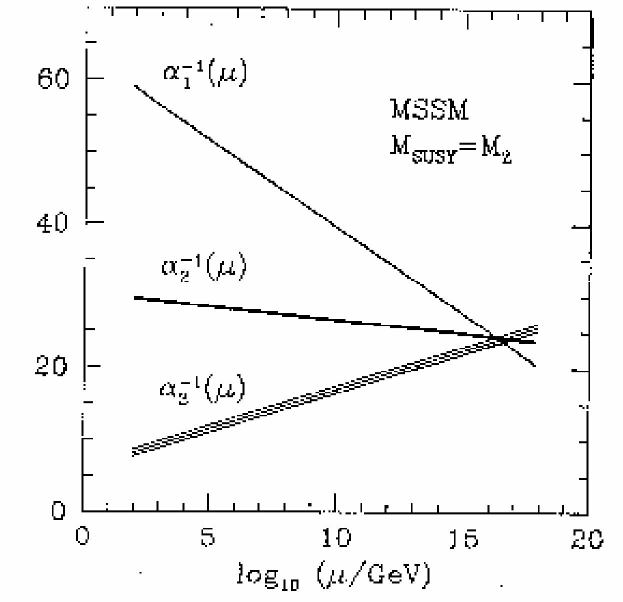
$\Delta(B-L)=2$ implies $\Delta L=2$ or Majorana neutrino

OR $\Delta B=2$ N-N-bar oscillation.

(RNM, Marshak,80)

Probing B-L scale and related physics

Note that SUSY at TEV SCALE + no new physics till 10^{16} GeV implies that coupling constants unify:



This suggests that perhaps local B-L is part of a grand unifying symmetry and it breaks at GUT scale. Related physics is GUT physics.

Does seesaw favor GUT scale B-L breaking ?

- **Atmospheric mass measured by Super-K can be related to B-L scale using the seesaw formula:**

$$\sqrt{\Delta m^2}_{atm} \approx \frac{m_t^{\,2}}{M_R}$$

assuming GUT relation for the 3rd generation that

$$m_D \approx m_t$$

This gives for the seesaw scale $M_R \approx 10^{14}\, GeV$

IN THIS CASE, SEESAW SCALE IS GUT SCALE and B-L PHYSICS IS GUT PHYSICS:

(modulo a mini fine tuning)

LOWER B-L SCALE POSSIBLE ?

However, Experiments do not tell us the value of m_D. if m_D is suppressed by some symmetries (e.g. family sym.), seesaw scale could be lower.

So two key questions in this connection now are:

- What is the physics associated with B-L symmetry in this case ?
- What is the scale of B-L symmetry ?

Message of this talk:

P-decay, N-N-bar osc.

and $\mu \rightarrow e + \gamma$ **will**

probe the scale of local

B-L sym.

P-decay if it is GUT scale

and N-N-bar if it is intermediate!!

HOW SO ?

$\Delta B \neq 0$ Modes and Their B-L

- P->e+ π^0 , P->K $\bar{\nu}$ mediated by the operator:

$$O_{\Delta B\neq 0} = \frac{1}{M^2} QQQL$$

Obeys $\Delta(B-L)=0$

Present lower limit on $\tau_{p->e+\pi^0} > 5\times 10^{33} yrs$

Implies $M \geq 10^{15} GeV$

This probes very high scales close to GUT scale.

B-L=2 Processes

- **Neutron-anti-neutron oscillations :**

PROBES INTERMEDIATE SCALES;

$$O_{\Delta B=2} = \frac{1}{M^5} u^c d^c d^c u^c d^c d^c$$

Leads to

$$\delta m_{n-\bar{n}} = O_{\Delta B=2} \Lambda_{QCD}{}^6$$

Or

$$\tau_{n-\bar{n}} = \hbar / \delta m_{n-\bar{n}} \sim M^5 / \Lambda^6$$

$giving \quad \tau_{n-\bar{n}} \sim 10^8 \sec.$ **for M=**$10^{5.5}\, GeV$

Beware: Power counting model dependent

- Depends on : (i) low energy symmetry (ii) TeV scale particle spectrum:

- TeV scale SUSY: sparticles < TeV scale

- Dominant P-decay operator $\tilde{Q}\tilde{Q}QL\frac{1}{M}$

Severely constrains SUSY GUTs :

N-N-bar operator $\frac{1}{M^3}\tilde{u}^c\tilde{d}^c d^c u^c \tilde{d}^c \tilde{d}^c$

Allows N-N-bar to probe new physics scales upto 10^9 GeV. There are much weaker suppressions possible in other models allowing probes till 10^11-10^12 GeV.

Phenomenology of N-N-bar Osc

$$i\hbar \frac{\partial}{\partial t}\begin{pmatrix} n \\ \bar{n} \end{pmatrix} = \begin{pmatrix} m+V_1 & \delta \\ \delta & m+V_2 \end{pmatrix}\begin{pmatrix} n \\ \bar{n} \end{pmatrix}$$

$$P_{n\to\bar{n}} \approx \left(\frac{\delta}{V_1 - V_2}\right)^2 Sin^2(V_1 - V_2)t$$

$$Two \quad cases:$$

$(i)(V_1 - V_2)t << 1:$ $\quad P_{n\to\bar{n}} \approx \left(\frac{t}{\tau_{n\bar{n}}}\right)^2$ free neutron oscillation;

$(ii)(V_1 - V_2) >> 1$ $\quad P_{n\to\bar{n}} \approx \left(\frac{\delta}{V_1 - V_2}\right)^2$ bound neutrons.

Present expt situation in N-N-bar Osc.

Range accessible to current reactor fluxes:

$$\tau_{n-\bar{n}} \sim 10^{8} - 10^{11}\,\text{sec}.$$

Present limit:ILL experiment: Baldoceolin et al. (1994)

$$\tau_{n-\bar{n}} \geq 10^{8}\,\text{sec}.$$

New proposal by Y. Kamyshkov, M. Snow et al for an expt.

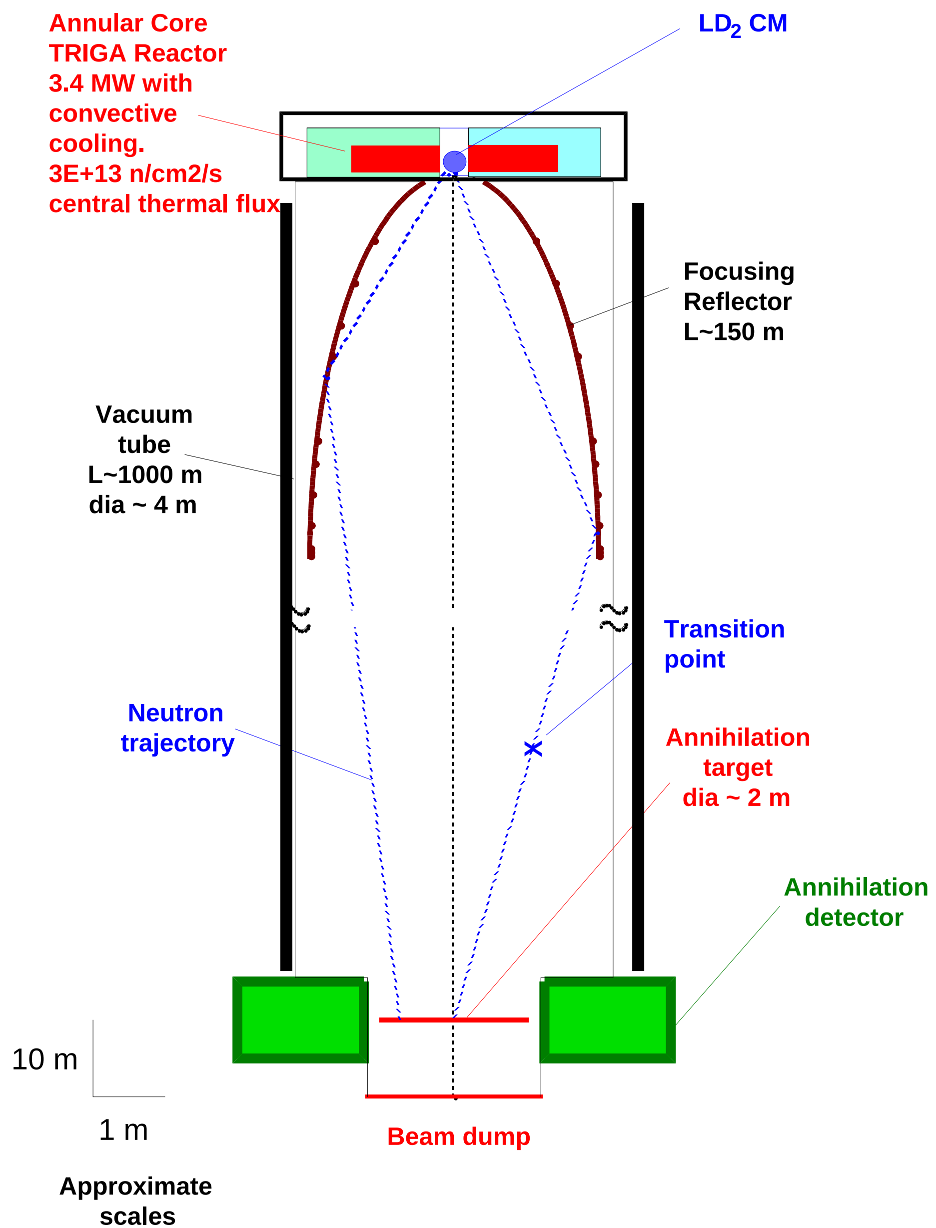
DUSEL GOAL: $10^{10} - 10^{11}\,\text{sec}.$

Figure of merit ~ $Flux \times \left(\frac{t}{\tau_{n-\bar{n}}}\right)^{2}$

Scheme of N-Nbar search experiment at DUSEL

- Dedicated small-power TRIGA research reactor with cold neutron moderator → v_n ~ 1000 m/s
- Vertical shaft ~1000 m deep with diameter ~ 6 m at DUSEL
- Large vacuum tube, focusing reflector, Earth magnetic field compensation system
- Detector (similar to ILL N-Nbar detector) at the bottom of the shaft (no new technologies)

Kamyshkov,Snow et al.



Two Examples of B-L Models

- **(A): SO(10) : the minimal GUT theory with B-L**
- **Georgi; Fritzsch and Minkowski (75)**

- **All fermions unified to one {16} dim rep.**

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

- **Breaks to MSSM below 10^16 GeV; B-L scale is GUT scale.**

Alternative B-L Unification

- Pati, Salam (74)
- **All 16 fermions unified under a partial unification group:** $SU(2)_L \times SU(2)_R \times SU(4)_c$

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

2. It also contains B-L symmetry for seesaw

3. Only restriction on B-L scale is nu mass and hence

$$M_{224} \approx 10^{11} GeV \rightarrow 10^{16} GeV$$

SO(10) vs $SU(2)_L X SU(2)_R X SU(4)_C$

HOW TO TELL WHETHER THEORY BEYOND MSSM IS G(224) WITH M= 10^{11} GeV;

OR

SO(10) WITH MU= 10^{16} GeV.

Proton decay vrs N-N-bar search can Tell the difference

Digression on GUTs and Proton decay

SU(5) as a Warm-up example:

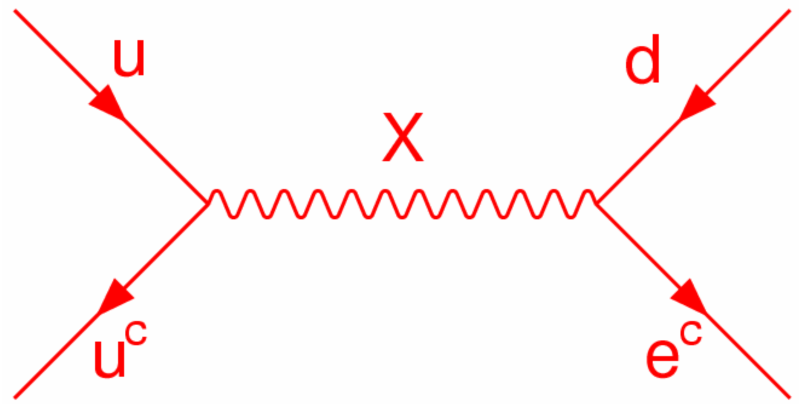
☞ The simplest GUT model (circa 1980s)

- Fermions: $5 = \begin{pmatrix} d^c \\ d^c \\ d^c \\ \nu \\ e^- \end{pmatrix}$ and $10 = \begin{pmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ & 0 & u_1^c & u_2 & u_3 \\ & & 0 & u_3 & d_3 \\ & & & & e^+ \\ & & & & 0 \end{pmatrix}$
- : Higgs $5 \oplus 5 \oplus 24$.
- Predicts: at M_U, $m_b = m_\tau$; very good prediction

  Also predicts $m_s = m_\mu$; $m_d = m_e$; VERY BAD PREDICTION!!
- No explanation of neutrino mass:
- PRETTY MUCH SU(5) DOES NOT WORK.

Nucleon Decay in Generic SUSY GUTs

- **Gauge Boson exchange:**



$$p \rightarrow e^+\pi^0,\ \tau_p^{-1} \approx \left[\frac{g^2}{M_X^2}\right]^2 m_p^5 \approx [10^{36\pm1} yr]^{-1}$$

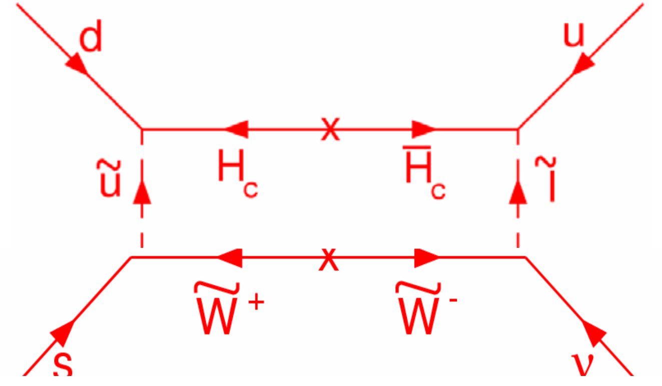
Sources of uncertainty:

Threshold effects, matrix element, $\alpha_s(m_Z)$

SUSY changes GUT scale dependence

- Sakai, Yanagida, Weinberg (1982)

$$O_{p-decay} \cong \frac{1}{M_U} QQ\tilde{Q}\tilde{L}$$



$$p \rightarrow \bar{\nu} K^+$$

$$\tau_p^{-1} \approx [\frac{f^2}{M_{H_c} M_{SUSY}}]^2 (\frac{\alpha}{4\pi})^2 m_p^5 \approx [10^{28} - 10^{32} yr]^{-1}$$

Minimal SUSY SU(5) is highly disfavored

- **Murayama, Pierce; Bajc, Perez, Senjanovic (02); Perez,Dorsner,Rodrigo(06)**

Predictions for proton decay in SO(10)-16

- **B-L could be broken either by {16}-H or {126}-H.**
- **SU(5) type problem avoided due to cancellation between diagrams.**
- **Proton decay in {16} models: highly model dependent: in one class of models**

(Babu, Pati and Wilczek (2000))

$$\tau(p \to \bar{\nu} K^{+}) \lesssim 10^{34} \text{ yr}$$
$$Br(p \to \mu^{+} K^{0}) \sim 10\%$$

Predictions for proton decay in SO(10)-126

- **Minimal SO(10) model with 10+126 which predict neutrino mixings:**
- **4 parameter model: predicts**

$$\tau(n \to \pi\bar{\nu}) \leq 13 \times 10^{32} yrs$$

$$\tau(n \to K^0\bar{\nu}) \leq 3 \times 10^{33} yrs$$

- **(Goh, R.N. M, Nasri, Ng (2004))**

Decay model $(p \to \bar{\nu}K^+)$ **highly suppressed .**

So again proton decay modes like these are highly model dependent.

Truly "model independent" prediction

- Gauge exchange mode P-> e+ π^0 , which is predicted in minimal GUT models to be around 10^36 years.

- "The true holy grail of grand unification"

STORY OF N-N-BAR OSCILLATION

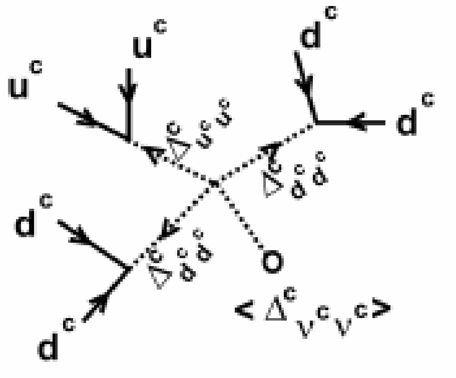
- In terms of standard model fields it scales like M^-5 and hence unlikely to probe scales beyond a 100 TeV. Are there plausible extensions of SM where one can probe realistic seesaw models wit higher scale ?
- Second question is: since such high dim operators go out of equilibrium only around the electroweak scale, are they not going to erase any preexisting baryon asymmetry-
- So how do we understand the origin of matter if N-N-bar is visible in expts. ?
- The answers to both questions -“YES”.

Testing Sub-GUT B-L with N-N-bar

- Recall with SM spectrum in the TeV range, NN operator is

$$\mathbf{O} = \frac{1}{M^5} u^c d^c d^c u^c d^c d^c$$

- Feynman diagram for N-N-bar Feynman noSUSY
- RNM and Marshak,80



- Tiny n-n-bar for M_{B-L}>100 TeV. Can n-n-bar test higher B-L scales ?

Things change with SUSY and new particles

A. Dominant operator with SUSY:

$$(u^c d^c \tilde{d}^c \tilde{u}^c \tilde{d}^c \tilde{d}^c / M^3)$$

Note weaker Seesaw suppression

B. SUSY + diquark Higgs field $\Delta_{u^c u^c}$, at TeV scale

then the effective operator is: $\Delta_{u^c u^c} d^c d^c \tilde{d}^c \tilde{d}^c / M^2$.

Dutta, Mimura and RNM, (2005)

Supression Still weaker !

C. If the TeV scale has $\Delta_{u^c d^c}$ fields, effective op. is

$$\Delta_{u^c d^c} \Delta_{u^c d^c} d^c d^c / M$$

Weakest Suppression

A G(224) theory for case B and N-N-bar

☞ **Fermion assignment:** $F_{L,R} \equiv \begin{pmatrix} u & u & u & \nu \\ d & d & d & e \end{pmatrix}_{L,R}$.

Case (i): Higgs set: $\phi(2,2,1) \oplus \Phi(2,2,15)$ **and** $\Delta^c(1,3,10) \oplus \bar{\Delta}^c(1,3,\overline{10})$: $\oplus\,\Omega(1,3,1)$

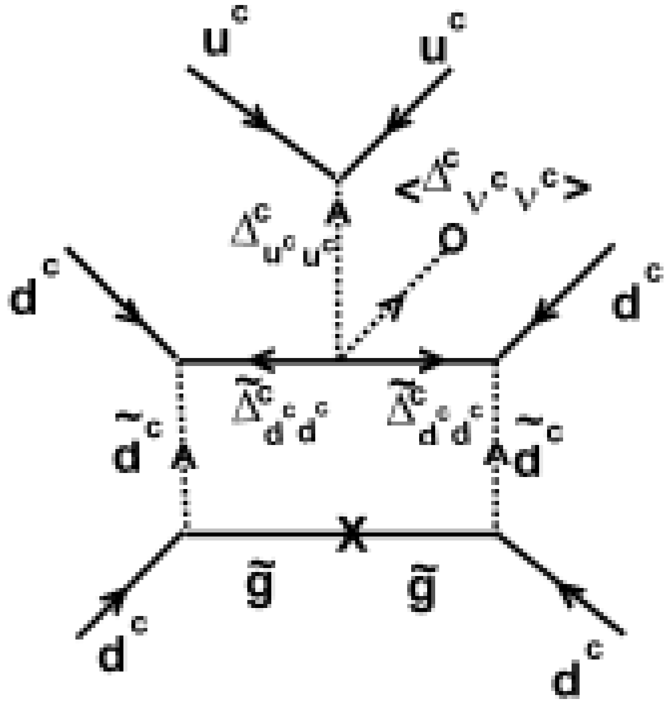
Superpotential :

$$W = M\Delta^c\overline{\Delta}^c + M'\Omega^2 + \lambda\Delta^c\Omega\overline{\Delta}^c$$

$$Large\ Global..Sym..Leaves..\Delta_{u^c u^c}...weakscale$$

Estimate of N-N-bar in Minimal 224 model:

- **New Feynman diagram for N-N-bar osc.**



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

$M_{seesaw} \sim 10^{11}$ GeV, typical f, λ, $\tau_{N-\bar{N}} \sim 10^{10}$ sec.

Observable N-N-bar osc (Dutta, Mimura, RNM (2006)

Other examples-Babu,RNM,Nasri-PRL (2007)

- 3x2 seesaw model with the third RH neutrino in the TeV scale and decoupled from the neutrino sector:
- Plus a pair of color triplets: X and X-bar with couplings:

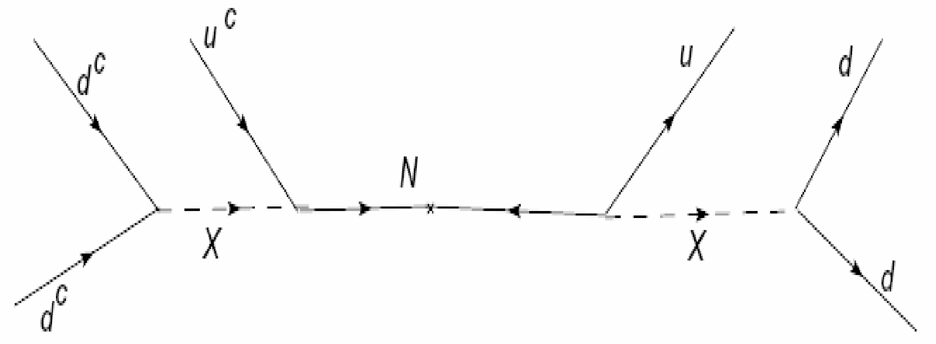
$$W = \lambda_i N u^c{}_i X + \lambda'_{kl} d^c{}_k d^c{}_l \overline{X} + M_N NN + M_X X\overline{X}$$

Impose R-parity symmetry as in MSSM.

This simple extension provides a remarkably natural model for dark matter, neutrinos and baryogenesis and has testable predictions !!

N-N-bar Prediction

- **N-N-bar oscillation: Diagram involves Majorana N exchange**



- **Effective strength:**

$$G_{\Delta B=2} \cong \frac{\lambda_1 \lambda'_{12}}{M^4{}_X M_N}$$

- **Will lead to N-N-bar osc via the s-content in neutron.**
- **Transition time expected to be around 10^8 sec.**

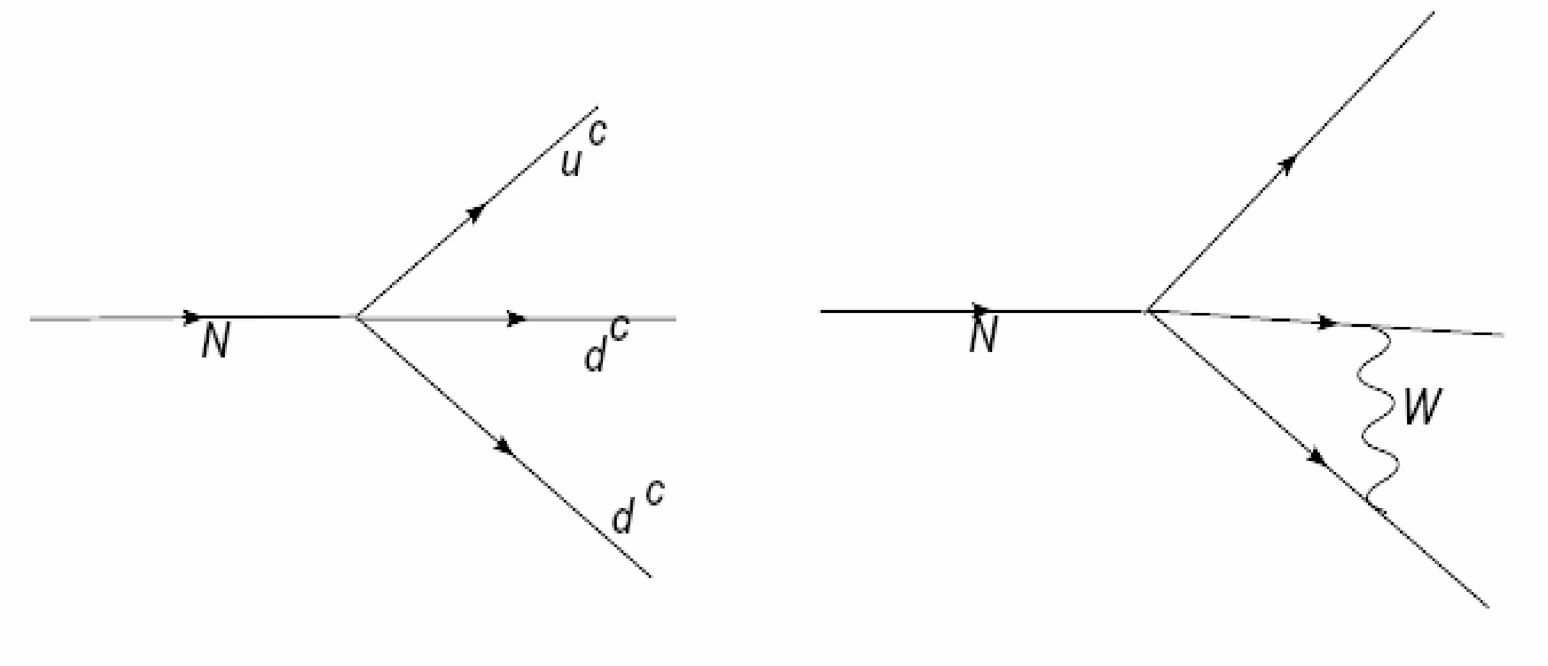
Baryogenesis in N-N-bar models

- **Usual argument : Any early universe baryon asymmetry will be erased by fast N-N-bar transitions being in equilibrium:**

Typical out of Equilibrium T is around 100 GeV. Need a mechanism for baryogenesis below the electroweak breaking scale.

Recent work which resolves this issue by post-sphaleron baryogenesis: Babu,RNM, Nasri PRL, (2006,2007)

Baryogenesis Diagrams in the second model



Possible to obtain right n_B/N_gamma

Other Examples:

- **Shrock and Nussinov (2001)**
- **Models with extra dimensions where fermions are localized in the fifth dimension lead to observable N-N-bar oscillation.**

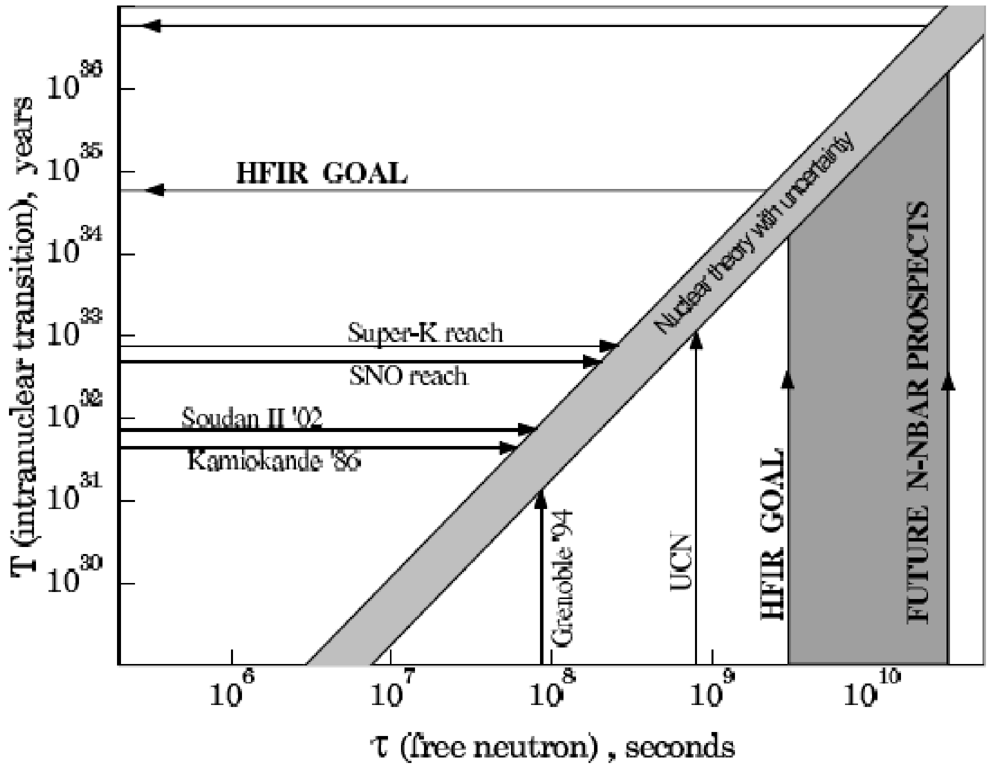
Proton decay vs N-N-bar oscillation

$N-\bar{N}$	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

Comparision P-decay vs N-N-bar

Comparison of free-neutron and bound-neutron methods

☞



Role of Lepton Flavor Violation

- **Standard model with Majorana neutrino mass without supersymmetry and high scale seesaw:**

$$B(\mu \to e + \gamma) \approx \frac{3\alpha}{32\pi}\left(\frac{m_\nu}{M_W}\right)^4$$

Very tiny:

With SUSY, things are different.

SUSY seesaw and FCNC effects

- Neutrino mixings induce slepton mixings at low scale via radiative corrections and hence FCNC effects.

- Slepton mixings are proportional to Yukawa mixings that go into the seesaw formula:

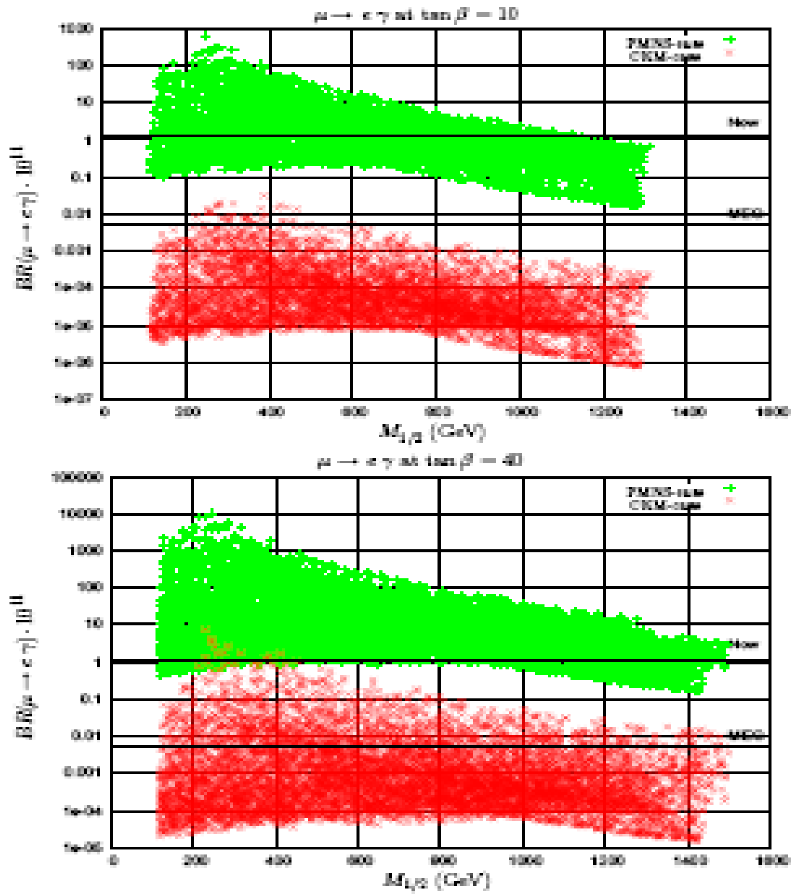
$$m_\nu \cong -m_D{}^T M_R{}^{-1} m_D \qquad m_D = Y_\nu v_{wk}$$

- Since neutrino masses are known, if M_R= fv_R (the B-L breaking scale) is lower , Y_nu will be smaller and hence will be the slepton mixing effects.

Generic predictions for $\mu \rightarrow e + \gamma$

$$V_{B-L} = 10^{14}\, GeV$$

Masiero, Vives, Vempati



Lower V_BL

- Branching ratio lower by v_BL square. So non-observation of any effect at MEG expt along with a positive signal for N-N-bar oscillation will indicate lower B-L scales.

Only exception is if B-L scale is the TeV range:

In this case even without SUSY, mu-> e +gamma Br. Can be observable.

Conclusion

- With the discovery of neutrino mass the case for N-N-bar oscillation is a lot stronger now than it was in the 1980s. Urge new search at the level of 10^10 sec to test for B-L seesaw scale around 10^11 GeV as against GUT scale seesaw.
- N-N-bar discovery will completely change the thinking on grand unification.
- As far as Proton decay goes, predictions below 10^36 yrs are model dependent; while they should be done, the true value of P-decay as a test of GUT idea is the 10^36 yrs level search and should be the ultimate goal.

Thank you for your attention.