PROBING B-L UNIFICATION via N-N-bar Oscillation

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Plan of the Talk

1. Why B-L symmetry ?

2. Two classes of local B-L models

3. N-N-bar Oscillations as tests of these models.

Why B-L Symmetry ?

- Standard model has global B-L symmetry.
- There are several hints that B-L sym exists beyond SM or MSSM.
- WE THEREFORE NEED TO KNOW:
- Nature of this symmetry ? global or local ?
- Broken or exact ? If broken, what is breaking scale and associated new physics ?
- N-N-bar Osc., one sure way to probe some of these issues !!

Hints of B-L from physics BSM

- **Neutrino mass, Seesaw and B-L:**

  Seesaw mechanism for small neutrino masses provides one of the strongest reasons for believing in B-L.

- **Dark matter in MSSM is natural if embedded into higher unified theory with local B-L.**

Neutrino mass, Seesaw and B-L

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

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

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

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

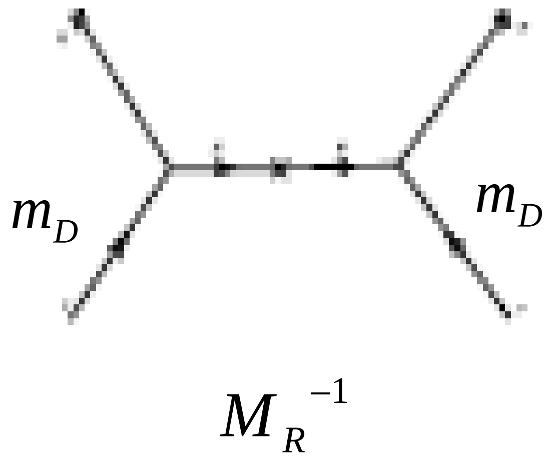
$$L = \begin{pmatrix} \nu \\ e^- \end{pmatrix} \sim (1, 2, \frac{-1}{2})$$

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

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

Why are neutrino masses tiny ?

Give ν^c a large Majorana mass:



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

Seesaw Mechanism:

Minkowski; Gell-Mann, Ramond, Slansky; Yanagida; Glashow; RNM,Senjanovic

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.

Dark matter and B-L sym.

MSSM allows R-parity violation that makes proton highly unstable and eliminates dark matter:

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

If B-L is a good symmetry beyond MSSM and breaks by two units R-parity is exact solving these problems.

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.

New electroweak symmetry with B-L

- **Gauge group**: $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$
- **Fermion assignment** $\begin{pmatrix} u_L \\ d_L \end{pmatrix} \overset{P}{\Leftrightarrow} \begin{pmatrix} u_R \\ d_R \end{pmatrix}$

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \overset{P}{\Leftrightarrow} \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$

- **Higgs fields:** $\phi(2,2,0)$ $;\Delta_R(1,3,+2) \oplus \Delta_L(3,1,+2)$
- **This theory when supersymmetrized give R-parity conservation naturally in MSSM**

Left-Right Symmetry breaking

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

$$\downarrow \quad < \Delta_R > \neq 0$$

$$M_{W_R}, M_{Z'} \neq 0$$

$$SU(2)_L \otimes U(1)_Y$$

$$\downarrow \quad < \phi > = \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' \end{pmatrix}$$

$$M_{W_L}, M_Z \neq 0; m_{q,l} \neq 0$$

$$U(1)_{em}$$

Electric Charge Formula

- **New Improved Formula for electric charge**

Standard model: $$Q = I_{3L} + \frac{Y}{2}$$

Y takes arbitrary values in SM.

On the other hand, in Left-right model

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

Every entry is physically determined.

(RNM, Marshak; Davidson,79)

Nu-mass and N-N-bar connection

New electric charge formula implies:

$$\Delta I_{3R} = -\frac{1}{2}\Delta(B-L)$$

Parity violation with $\Delta I_{3R} = 1$ gives

$\Delta(B-L) = 2$; This has two implications:

(i) $\Delta L = 2$ ---Majorana neutrino

(ii) $\Delta B = 2$ ---N-N-bar oscillation:

Majorana NU-MASS VIA SEESAW STRONGLY SUGGESTS N-N--BAR OSCILLATION.

Questions for N-N-bar Oscillation

- Neutrino mass is L=2; how does this imply a B=2 process ?

  Answer: quark lepton unification transmits L=2 to B=2.
- Are there decent theories EMBEDDING THE SEESAW MECHANISM where a viable Seesaw scale leads to observable N-N-bar oscillation ?
- Is it cosmologically safe to have observable N-N-bar oscillation ?
-

(Babu's talk)

Phenomenology of N-N-bar Osc

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

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

$Two \quad cases:$

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

$(ii)(V_1 - V_2) >> 1$ $\qquad P_{n\to\bar{n}} \approx \left(\frac{\delta}{V_1 - V_2}\right)^2$ 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, Dubbers et al. (1994)**

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

New proposal (see talks by Y. Kamyshkov, M. Snow, Young) for an expt. In DUSEL

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

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

Operator analysis of N-N-bar

To see what is probed by N-N-bar, do operator analysis for $\Delta B = 2$ processes:

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

Note M^5 suppression

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

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

$$giving \quad \tau_{n-\bar{n}} \sim 10^8 \sec. \quad M \approx 10^{5.5} GeV$$

Scale Reach of N-N-bar

- Is the scale reach of N-N-bar limited to only 300 TeV in generic models as suggested ?
- NO- once new physics at TeV scale is entertained e.g. SUSY, new Higgs !

Weaker suppression with SUSY

A. **Dominant operator with SUSY:**

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

Can probe M_B-L upto 10^9 GeV

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)

Probe M_{B-L} to 10^12 GeV.

Two Generic B-L Scenarios and N-N-bar

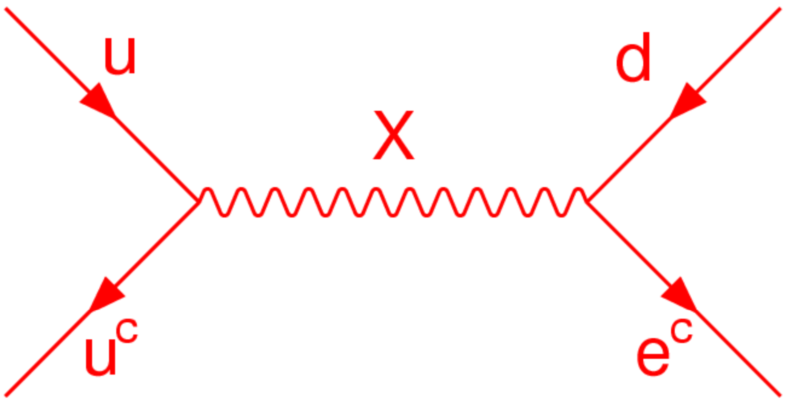
- (A): SO(10) : the minimal GUT theory with B-L motivated by Gauge coupling unification:
- Georgi; Fritzsch and Minkowski (75)
- All fermions unified to one {16} dim rep.

$$\begin{pmatrix} u \\ u \\ u \\ d \\ d \\ d \\ \nu \\ e \\ u^c \\ u^c \\ u^c \\ d^c \\ d^c \\ d^c \\ \nu^c \\ e^c \end{pmatrix}$$

- Breaks to MSSM below 10^16 GeV;
- B-L scale is GUT scale due to unification. N-N-bar suppressed and unobservable.

Nucleon Decay in Generic SUSY GUTs

- **Key test of GUTS: Gauge Boson mediated p-decay:**



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

Sources of uncertainty:

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

Lower life time predictions are highly model dependent **(Talks by Nath, Pati, Perez)**

Alternative B-L Unification

- Pati, Salam (73)
- **Only 16 fermions unified but not gauge couplings:**

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

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

2. Cantains B-L for seesaw; Only restriction on B-L scale is nu mass (not coupling unification) and hence

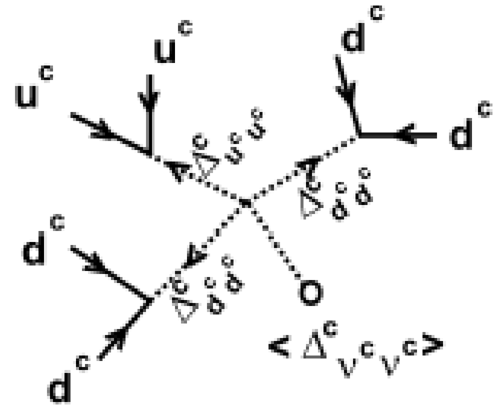
$$M_{224} \approx 10^{11} GeV \to 10^{16} GeV$$

N-N-bar can be observable in this case ;

No proton decay.

Non-SUSY G(224) and N-N-bar

- **The Feynman diagram for N-N-bar in Non-SUSY 224 model** **(RNM, Marshak, 80)**



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

- Δ^4 **vertex needed for baryogenesis .**
- **With M=** $M_\Delta \approx M_{B-L}$ **N-N-bar observable only if** $M_{B-L} \approx 10^{5.5-6} GeV$

A SUSY G(224) theory 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** $\Delta^c(1,3,10) \oplus \bar{\Delta}^c(1,3,\bar{10})$: $\oplus\, \Omega(1,3,1)$

$$Superpotential:$$

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

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

SUSY makes N-N-bar observable

- **Two points:**

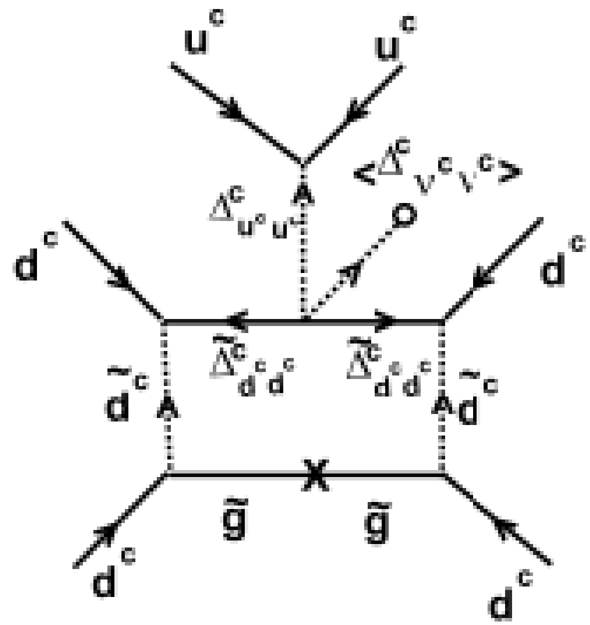
- **(i)** $\Delta_{u^c u^c}$ **naturally at 100 GeV scale due to accidental global symmetry caused by supersymmetry-**

- **(ii) Power suppression is** $\dfrac{1}{M_{B-L}{}^2}$

rather than 1/M^5 (as in non-susy case). Improves observability of N-N-bar osc.

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 for M_seesaw~10^11 GeV.

(Dutta, Mimura, RNM; PRL (2006)

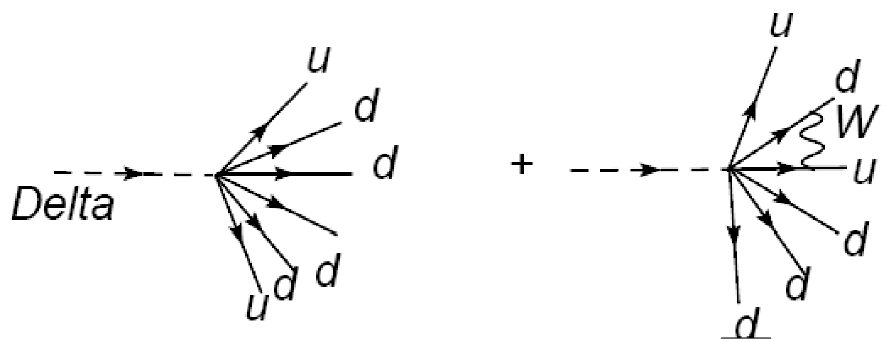
Origin of matter in N-N-bar models

- **Usual argument : Early universe baryon asymmetry erased by fast N-N-bar being in equilibrium:**

  --hard to generate baryons: NOT TRUE

--e.g. NonSUSY NNbar model: No leptogenesis; Out of eq. temp for NNbar operator is: 10 TeV;

New source of baryon asymmetry:



post-sphaleron baryogenesis: Babu,RNM, Nasri PRL, (2006,2007);

Proton decay vs N-N-bar oscillation

$N-\bar{N}$	P-decay
Probes $M_{seesaw} \lesssim 10^{11}$ 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

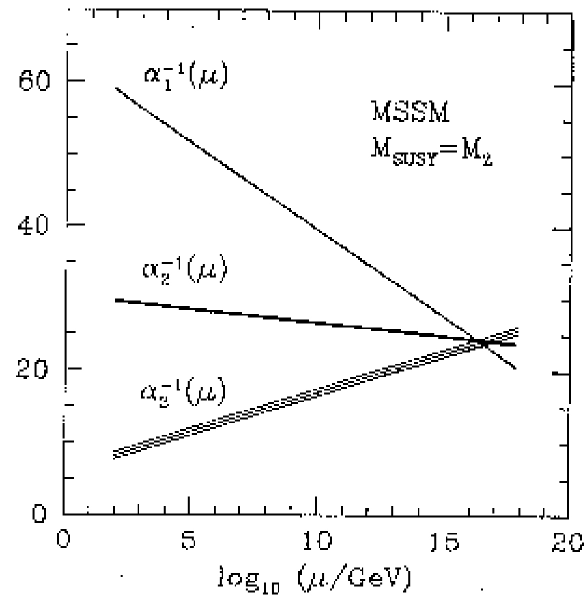
Conclusion

- With the discovery of neutrino mass the case for N-N-bar oscillation is a lot stronger now than before. Urge new search at the level of 10^10 sec to test for B-L seesaw scale around 10^11 GeV or less vs 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.

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.

$\Delta B \neq 0$ 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 $\tau_{p->e+\pi^0} > 5\times 10^{33} yrs$

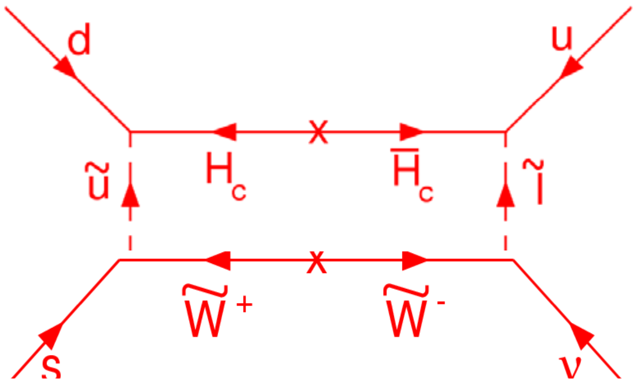
Implies $M \geq 10^{15} GeV$

This probes very high scales close to GUT scale.

SUSY changes GUT scale dependence

- Sakai, Yanagida, Weinberg (1982)

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



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

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

Minimal SUSY SU(5) is highly disfavored

- **Murayama, Pierce; Bajc, Perez, Senjanovic (02); Nath, Perez review (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**

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

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

- **(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.

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:

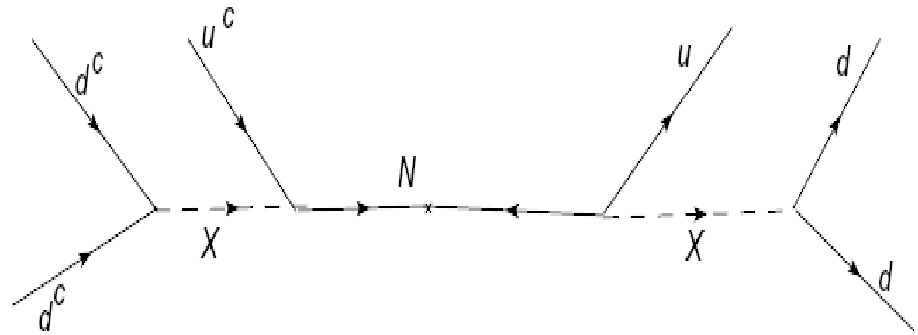
$$W = \lambda_i N u^c{}_i X + \lambda'_{kl} d^c{}_k d^c{}_l \overline{X} \; + \; M_N NN + M_X X\overline{X}$$

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**

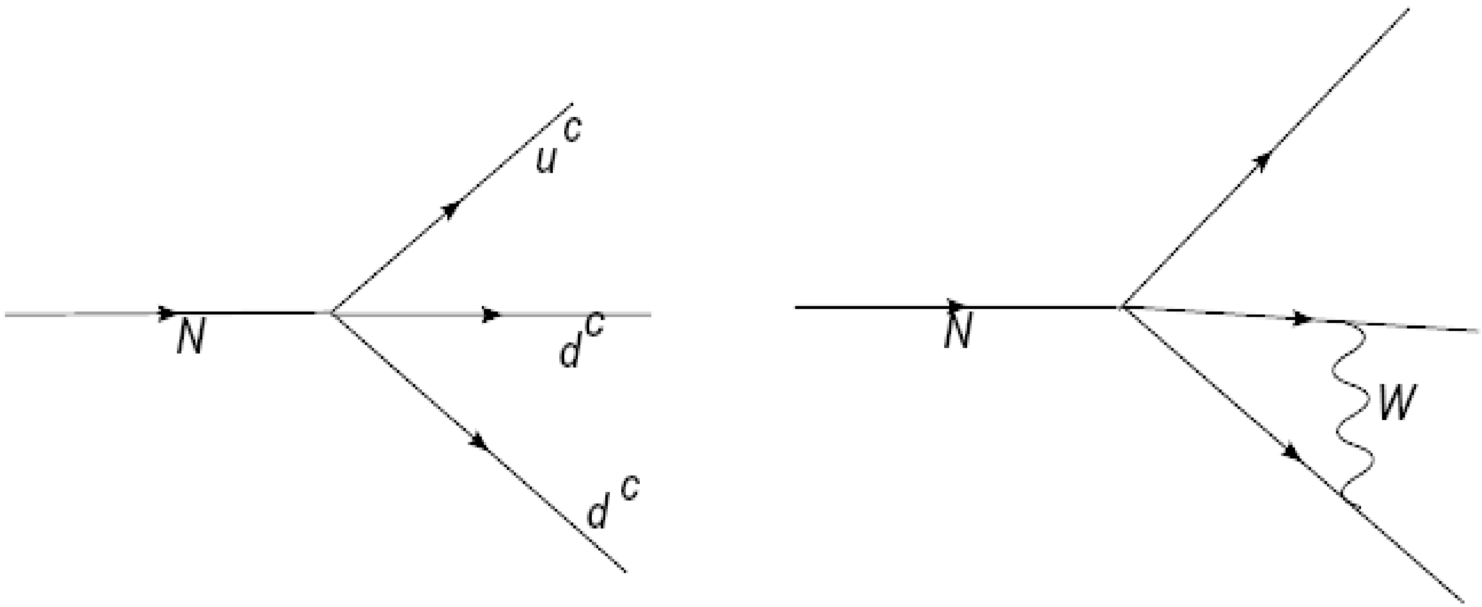


- **Effective strength:**

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

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

Baryogenesis Diagrams in the second model



Possible to obtain right n_B/N_gamma

Comparision P-decay vs N-N-bar

Comparison of free-neutron and bound-neutron methods

☞