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Unification of dark matter and baryogenesis

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Unification of Dark matter and Baryogenesis

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Phys. Rev. Lett, 97 (2007)
(K.S.Babu, R. N. Mohapatra, S.N)

July 23, 2007

- Neutrinos have mass

{Homestake, SAGE, GALLEX, SNO, SK, Soudan II, MACRO, K2K, MINOS, KamLAND, CHOOZ, ..}

parameter	best fit	3σ range
Δm^2_{21} $[10^{-5}\ \mathrm{eV}^2]$	7.9	7.1–8.9
Δm^2_{31} $[10^{-3}\ \mathrm{eV}^2]$	2.6	2.0–3.2
$\sin^2\theta_{12}$	0.30	0.24–0.40
$\sin^2\theta_{23}$	0.50	0.34–0.68
$\sin^2\theta_{13}$	0.00	≤ 0.040

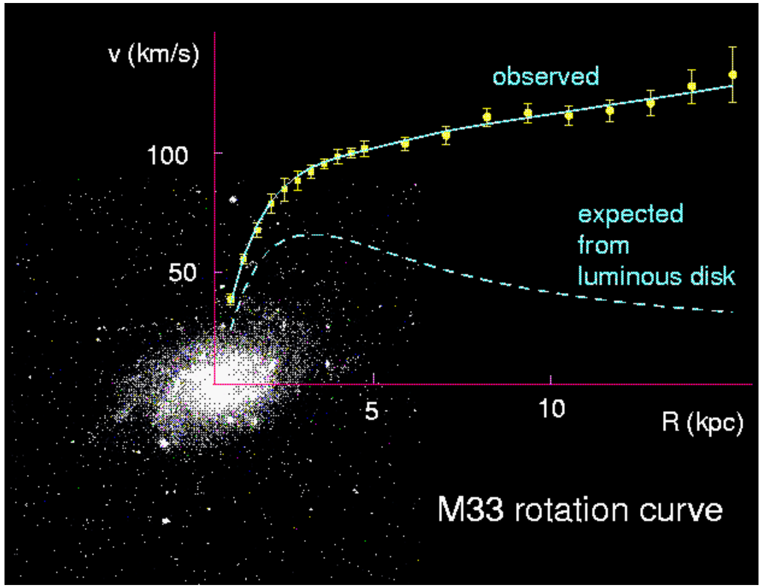
- In standard model $m_\nu = 0$
- Need to extend the SM :

1. Higgs sector: $SU(2)$ Triplet $\Delta \to$ Type *II* see-saw
2. Fermion sector: $\begin{cases} \textit{SM singlet } (\nu_R) \to & \text{Type I see-saw ;} \\ SU(2)\ \textit{triplet} \to & \text{Type III see-saw.} \end{cases}$

P. Minkowski 1977;
M. Gell-Mann, P. Ramond and R. Slansky (1979);
R.N.Mohapatra and G. senjanovic (1980); Ma (1998).

- Most of the matter in the universe is dark

  - Rotation curves of spiral galaxies



  - measurement of X-ray emission from the hot gas in clusters
  - Gravitational lensing
  - SDSS + 2dGRS
  - WMAP + SNIa + BBN

$$\Rightarrow \Omega_{DM} h^2 \simeq 0.11$$

Baryogenesis

- our solar system is made entirely from matter.
- $\overline{p}$ are observed in the cosmic rays : $n_{\overline{p}}/n_p \sim 10^{-4}$ but are likely to be understood as secondaries in $p + p \longrightarrow 3p + \overline{p}$
- On larger scale if there were both matter and anti-matter galaxies in one cluster there would be a strong γ-ray from

$$N\overline{N} \longrightarrow \pi' s \longrightarrow \gamma' s$$

$\Rightarrow L_M \gg 1000\ Mpc$ $A.Cohen, S.Glashow, A.DeRujula$

Astrophys. J. 495 (1998)

- The abundance of matter over anti-matter is measured by the baryon asymmetry:

$$\eta = \frac{n_B - n_{\overline{B}}}{s} \simeq 0.8 \times 10^{-10} \ \ \{BBN,\ WMAP\}$$

Sakharov's Conditions

A. D. Sakharov
JETP Lett.5 (1967)

- Baryon number violation
- C and CP violation
- Departure from thermal equilibrium

- Electroweak baryogenesis

Qualitatively the SM satisfies the 1^{st} and 2^{nd} ingredients, and the 3^{rd} requires the phase transition to be first order. However quantitatively it does not work in the SM because:

$$(a) \quad The\ EWPT\ is\ too\ weak(\frac{v(T_c)}{T_c} > 1 \Rightarrow m_H < 40\ GeV)$$

$$(b) \quad CP\ violation\ is\ too\ small\ (\sim 10^{-20}!!)$$

May be the *MSSM*:

- $m_{\tilde{t}_R} \leq 172\ GeV$
- $m_H < 120\ GeV$
- $m_{\tilde{Q}} = 100\ GeV \exp\{\frac{1}{9.2}\left(\frac{m_H}{GeV} - 85.9\right)\}$

Carena, Quiros, Wagner; **Nucl.Phys.B 524 (1998)**
J. Cline , G. Moore; **Phys. Rev. Lett 81 (1998)**

- GUT Baryogenesis with $\Delta(B-L)=0$

Here the baryon asymmetry is generated from the out of equilibrium decay of heavy GUT gauge boson or heavy colored triplet Higgs. eg:

$$X \rightarrow lq; qq$$

where $X \in GUT/SM$.

However above the EWPT the sphalerons transition rate is

$$\Gamma_{sph} \simeq \alpha_W^5 T \simeq 10^{-6} T$$

Any BAU generated around the GUT scale gets erased by the very rapid sphaleron processes at $T \sim 10^{12}\ GeV$

- Leptogenesis

The idea is that

Fukugita and T. Yanagida **Phys. Lett. B 174 (1986)**

- initially ($T_i \gg 100 GeV$) : $\{B_i = 0; L_i \neq 0; and\ \Delta(B-L)_i \neq 0\}$ This can happen for example due to the decay of a heavy right handed neutrino
- As the universe cools down to $T_{EW} \sim 100\ GeV$, the $(B-L)$ asymmetry gets reprocessed into a baryon asymmetry thanks to the sphaleron interactions:

$$\eta_B = 0.35 \eta_{B-L}$$

J. Harvey, M. Turner **Phys. Rev. D 42 (1990)**

- requires the lightest RH neutrino mass $M_1 \geq 3 \times 10^9\ GeV$
  Davidson and Ibarra **Phys. Lett. B 535 (2002)**
- Tension with Supergravity: $T_{RH} < 3 \times 10^7\ GeV$
  Kohri, Moroi, Yotsuyanagi **Phys. ReV. D 73 (2006)**

many extensions of the standard model based on left-right symmetry (e.g $SU(4)_c \times SU(2)_L \times SU(2)_R$) or $SO(10)$ GUT model, predict the existence of

- $\Delta B = 1$

- $\mathcal{L}^{NON-SUSY}_{\Delta B=1} \sim \frac{1}{\Lambda_6^2}\{QQQL; \;\; QQu_R e_R; \;\; QLu_R d_R\}$

- $\mathcal{L}^{SUSY}_{\Delta B=1} \sim \frac{1}{\Lambda_5}\{(QQQL)_F ; \;\; \left(U^C U^C D^C E^C\right)_F\}$

$\Rightarrow p \rightarrow l^+ + M^0 \;, \; p \rightarrow \overline{\nu} + K^+$
$\tau_p > 10^{33}\ yrs \Rightarrow \Lambda_6 > 10^{15}\ GeV \;;\; \Lambda_5 > 10^{25}\ GeV$

- $\Delta L = 2$

- $\mathcal{L}_{\Delta L=2} \sim \frac{1}{\Lambda_N}(LH)^2$

$\Rightarrow m_\nu \sim \frac{<H>^2}{\Lambda_N}$
$max\{m_{\nu_2}, m_{\nu_3}\} \sim 10^{-1.5} \Rightarrow \Lambda_N \sim 10^{14}\ GeV$

- $\Delta B = 2$

- $\mathcal{L}^{NON-SUSY}_{\Delta B=2} \sim \frac{1}{\Lambda_9^5} u_R d_R d_R u_R d_R d_R$
- $\mathcal{L}^{NON-SUSY}_{\Delta B=2} \sim \frac{1}{\Lambda_9^5} QQd_R QQd_R$
- $\mathcal{L}^{NON-SUSY}_{\Delta B=2} \sim \frac{1}{\Lambda_9^5} QQu_R d_R d_R d_R$
- $\mathcal{L}^{SUSY}_{\Delta B=2} \sim \frac{1}{\Lambda_7^3} \left(U^C D^C D^C U^C D^C D^C\right)_F$
- $\mathcal{L}^{SUSY}_{\Delta B=2} \sim \frac{1}{\Lambda_8^3} \left(QQ\overline{U^C D^C D^C D^C}\right)_D$
- $\mathcal{L}^{SUSY}_{\Delta B=2} \sim \frac{1}{\Lambda_8^3} \left((QQ)(QQ)\overline{D^C D^C}\right)_D$

$n \leftrightarrow \overline{n}$

$\tau_{n\overline{n}} > 10^8\ s \Rightarrow \Lambda > 10^5\ GeV$

PROBE NEW PHYSICS AROUND TeV SCALE

New Model

- Extend the MSSM with:
  - Two heavy ($\gg TeV$) and one light ($< TeV$) RH neutrinos
  - Pair of colored triplets $(X, \overline{X})$
- $W = \lambda_1^i N u_i^c X + \lambda'_{ij} d_i^c d_j^c \overline{X} + M_N \overline{N} N + M_X \overline{X} X$
- Can be obtained from GUT such as $SU(5)$:
  $\rightarrow (X, \overline{X}) \in (\overline{10_H}, 10_H)$
  $\rightarrow$ Coupling unification not affected; $\delta\alpha_U / \alpha_U \sim 1$
- Assumptions:
  - $M_{X,\overline{X}} \sim TeV$
  - $M_{N_1} < M_{\widetilde{q},\widetilde{l},\widetilde{B},..}$
- $$\begin{cases} \widetilde{N_1}, \ \textit{is stable} \Rightarrow & \text{DM candidate;} \\ N_1 \ \textit{is unstable} \Rightarrow & \text{BAU.} \end{cases}$$

- The Lagrangian including soft SUSY breaking terms:

$$\bullet -\mathcal{L}_{\rm scalar} = |M_X|^2(|X|^2 + |\overline{X}|^2) + m_X^2|X|^2 + m_{\overline{X}}^2|\overline{X}|^2 + (B_X M_X X\overline{X} + h.c) + |M_N|^2|\tilde{N}|^2 + m_{\tilde{N}}^2|\tilde{N}|^2 + (\frac{1}{2}B_N M_N \tilde{N}\tilde{N} + h.c.)$$

- Two mass eigenstates X_1 and X_2 :

$$X = \cos\theta X_1 - \sin\theta e^{-i\phi} X_2;$$
$$\overline{X}^* = \sin\theta e^{i\phi} X_1 + \cos\theta X_2$$

- $\tan 2\theta = \frac{|2B_X M_X|}{|m_X^2 - m_{\overline{X}}^2|}$; $\phi = \mathrm{Arg}(B_X M_X)\mathrm{sgn}(m_X^2 - m_{\overline{X}}^2)$.

- The two mass eigenvalues are

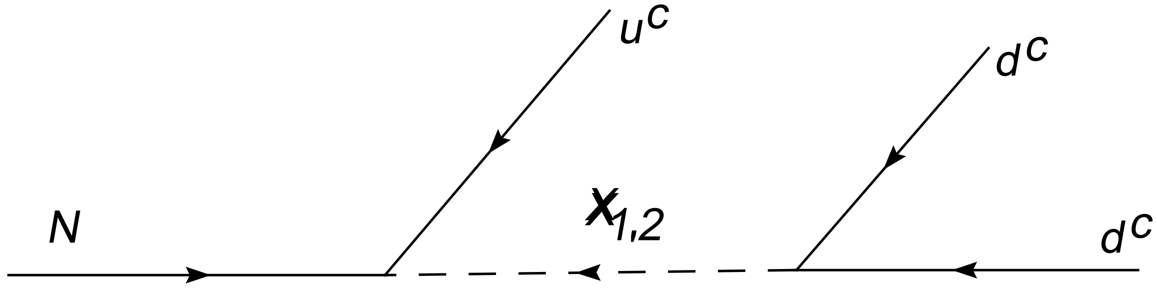
$$M^2_{X_{1,2}} = |M_X|^2 + \frac{m_X^2 + m_{\overline{X}}^2}{2} \pm \sqrt{\left(\frac{m_X^2 - m_{\overline{X}}^2}{2}\right)^2 + |B_X M_X|^2}$$

- The two *real* mass eigenstates from the $\tilde{N}$ field :

$$M^2_{\tilde{N}_{1,2}} = m^2_{\tilde{N}} + |M_N|^2 \pm |B_N M_N|$$

- Sakharov's 3^{rd} condition :

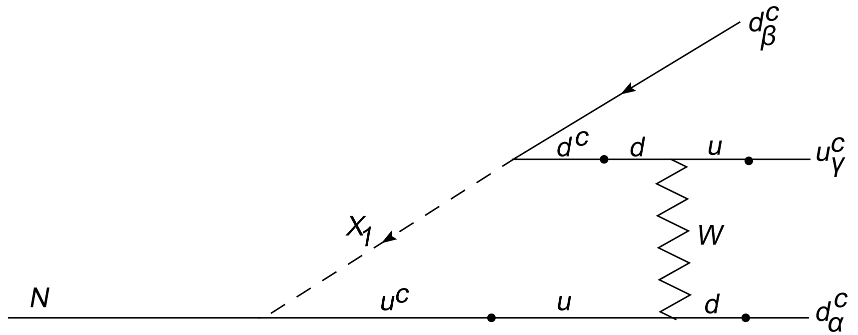
$$\Gamma(N \rightarrow d^c d^c d^c + h.c) \leq \sqrt{g_*}\frac{T^2}{M_{Pl}}$$



$$\Gamma_N = \frac{3}{64}\frac{(\lambda^\dagger\lambda)\mathrm{Tr}[\lambda'^\dagger\lambda')]}{192\pi^3} M_N^5 \sin^2 2\theta \left(\frac{1}{M_{X_1}^2} - \frac{1}{M_{X_2}^2}\right)^2$$

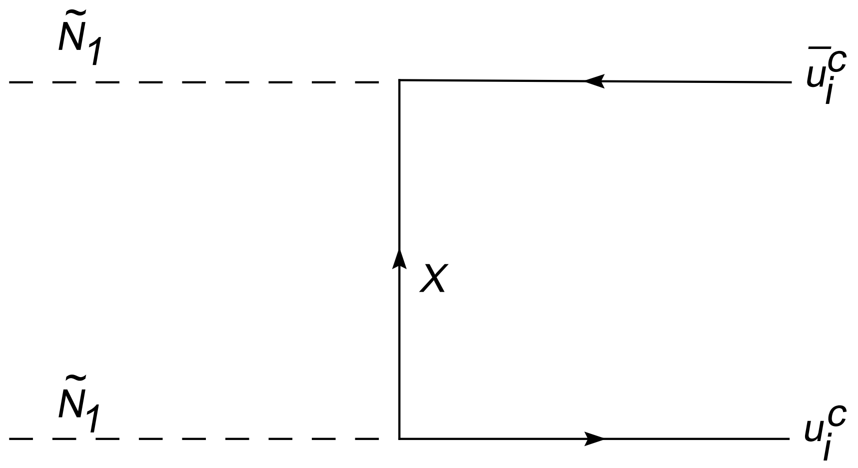
- For
  - $\sqrt{(\lambda^\dagger\lambda)\mathrm{Tr}[\lambda'^\dagger\lambda']} \sim 10^{-3}$
  - $M_N \sim 100\ GeV$
  - $M_{X_1} \sim\ TeV$

  $\Rightarrow$ N decays out of equilibrium at $T \sim M_N$
- N decay to $3q$'s and $3\overline{q}'s$ due to interference between tree and one loop (Babu, Mohapatra, S.N ,Phys. Rev. Lett(2006))



$$\epsilon \equiv \frac{\Gamma(N \to 3q^c) - \Gamma(N \to 3\overline{q^c})}{\Gamma_T} \simeq (-\alpha_2/4)\frac{(m_c m_t m_s m_b)}{(m_W^2 m_N^2)}$$

' $\Rightarrow \eta \sim 10^{-10}$

- Relic density:
  - 

  - $\sigma(\tilde{N}_1 \tilde{N}_1 \to q\overline{q}) v_{\rm rel} = \frac{3(\lambda^\dagger \lambda)^2}{8\pi s} \left(\frac{a}{b} \tanh^{-1}(\frac{b}{a}) - 1 \right)$

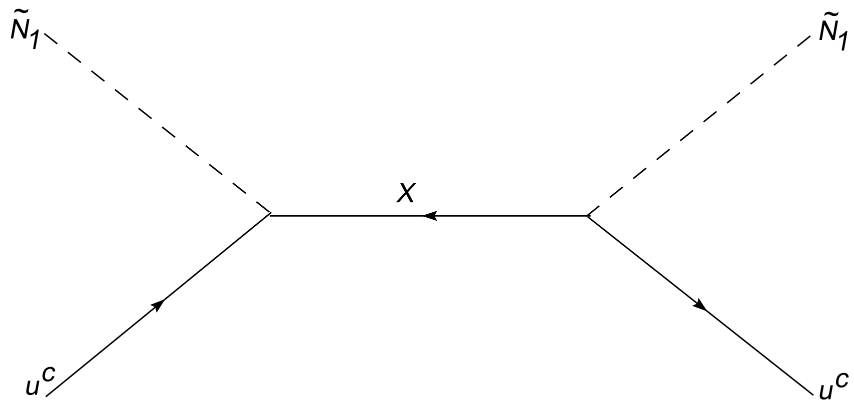
where

$$a = 2E^2 - M^2_{\tilde{N}_1} + M^2_X; \quad b = 2E|\overrightarrow{p}| \ .$$

  - For $\lambda_3 \sim 1/3$, $M_{\widetilde{N_1}} \sim 300 \ GeV$, $M_X \sim 500 \ GeV$

$$\Rightarrow \Omega_{\widetilde{N_1}} h^2 \simeq 0.1$$

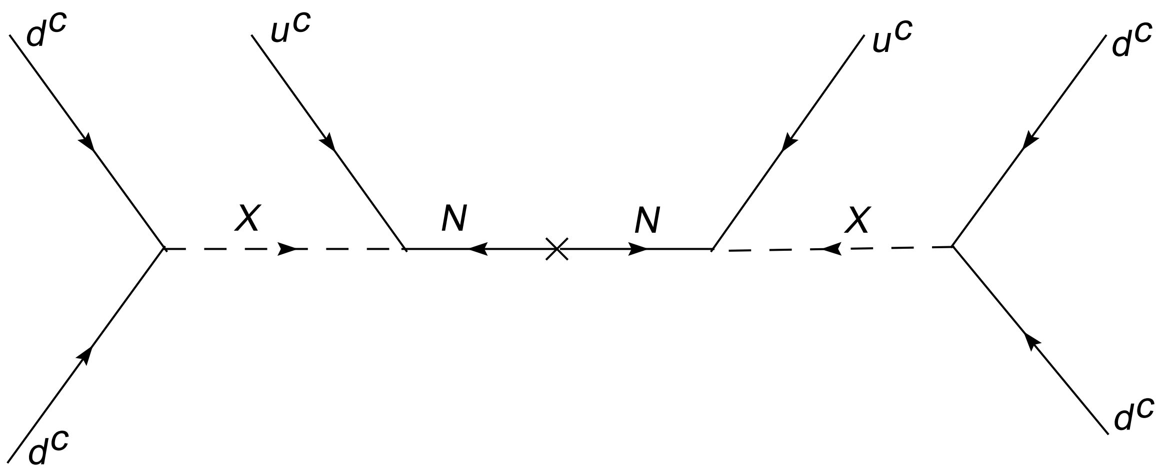
- Direct detection:

  - 

  - $\sigma_{\tilde{N}_1+p} \simeq \dfrac{|\lambda_1|^4 m_p^2}{4\pi M_X^4}\left(\dfrac{A+Z}{A}\right)^2$

  - For $\lambda_1 \sim 0.1,\ M_X \sim 500\ GeV$
$\sigma_{\tilde{N}_1+p} \simeq 10^{-8}\ pb \Rightarrow$ within the reach of SuperCDMS

Neutron-antineutron oscillation

- 

- $O_{\Delta B=2} = \frac{(\lambda_1 \lambda'_{12})^2}{M_N M^4_{\widetilde{X}_1}} (u^c d^c s^c)(u^c d^c s^c)$
- Will lead to $n - \overline{n}$ oscillation via the s-content in neutron
- If the strange content is $\sim 1\%$ $\Rightarrow \tau_{n\bar{n}} \sim 10^9\ sec$

- The Hamiltonian of the neutron-antineutron system is

$$\widehat{H} = \begin{pmatrix} E_n - i\frac{\Gamma_n}{2} & \delta m \\ \delta m & E_{\overline{n}} - i\frac{\Gamma_{\overline{n}}}{2} \end{pmatrix}$$

where E_n and $E_{\overline{n}}$ are the neutron and antineutron energies:

$$E_n \simeq m_n + \frac{p^2}{2m_n} + V_n$$
$$E_{\overline{n}} \simeq m_{\overline{n}} + \frac{p^2}{2m_{\overline{n}}} + V_{\overline{n}}$$

CPT invariance $\Rightarrow m_n = m_{\overline{n}} = m$ and $\Gamma_n = \Gamma_{\overline{n}} = \Gamma$
V_n and $V_{\overline{n}}$ are the potential felt by V_n and $V_{\overline{n}}$ respectively.

- In practice $V_n - V_{\overline{n}} \neq 0$
Long time ago (1979) Glashow pointed out that due to earth magnetic field

$$V_n = -V_{\overline{n}} \equiv V = \mu_n . B_{earth} \neq 0$$

$$\mu_n \simeq -2(\frac{e}{2m_n}) \simeq -6 \times 10^{-12}\ eV/Gauss$$

$$B_{earth} \simeq 0.5\ Gauss$$

$\Rightarrow \; V \simeq 3 \times 10^{-12} \; eV$

Hence the effective Hamiltonian reads

$$\widehat{H} \simeq \begin{pmatrix} m + V & \delta m \\ \delta m & m - V \end{pmatrix}$$

- The eigenstates are

$$\begin{aligned} |n_1 > &= \cos\theta |n > + \sin\theta |\overline{n} > \\ |n_2 > &= -\sin\theta |n > + \cos\theta |\overline{n} > \end{aligned}$$

where

$$\begin{aligned} \sin^2 2\theta &= \frac{\delta m^2}{\delta m^2 + V^2} \\ m_{\pm} &= m \pm \sqrt{\delta m^2 + V^2} \end{aligned}$$

$$\Rightarrow \; P_{n \rightarrow \overline{n}}(t) = \frac{\delta m^2}{\delta m^2 + V^2} \sin^2 \omega t$$

where

$$\omega = \frac{\sqrt{\delta m^2 + V^2}}{\hbar}$$

- If $\omega t \ll 1$, neutrons will behave essentially like free neutrons. This is called the quasi-free neutron condition. In this case

$$P_{n\to\overline{n}}(t) \simeq \frac{\delta m^2}{\hbar^2} t^2 = (\frac{t}{\tau_{n\overline{n}}})^2$$

Experiments that search for $n \leftrightarrow \overline{n}$ using free neutrons must satisfy

• Good screening against external fields in order to satisfy the quasi-free cond

• Very large neutron flux

• Long flight time , at the same time satisfying the quasi-free neutron condition.

The principle of such a measurement is simple:

- A beam of cold , quasi-free neutrons from reactor passes along a path L and then meets a target (eg. Carbon foil).
- The anti-neutrons formed during the flight time t annihilate in the target creating pions which are detected in the detector. The neutrons pass through the foil largely unhindered.
- A typical $\overline{n}$ signal consists of $5\ \pi' s$ with a total energy $\simeq 1.8\ GeV$ and a vanishing total momentum.
- The detector must be shielded against cosmic rays.
- Degaussing the earth magnetic field (factor $\sim 10^{-4}$)

In this case:

$$\frac{\overline{N}}{N} = \left(\frac{t}{\tau_{n\bar{n}}}\right)^2$$

$$\tau_{n\bar{n}} = \sqrt{\frac{I.T}{\overline{N}}\frac{L}{v_n}}$$

I : *the intensity of the neutron beam,*

T : *the running time of the experiment*

v_n : *the neutron velocity*

L : *the neutron drift length*

- $n \leftrightarrow \bar{n}$ were searched for at the Institut Laue Langevin" (ILL), in Grenoble, using cold neutrons, from $P = 58\ MW$ reactor with kinetic energy $K_n \simeq 2 \times 10^{-3}\ eV(v_n \simeq 600\ m/s)$, $L = 76\ m$ ($\Rightarrow t_{OF} \simeq 0.11\ s$) and intensity $I \simeq 10^{11}\ n/s$.

- The earth magnetic field was reduced (using shielding) from

$$0.5\ Gauss \longrightarrow 10^{-4}\ Gauss$$

$$\Rightarrow \ \delta E < 10^{-15}\ eV$$

after one year of running the Grenoble experiment achieved

$$\tau_{n\bar{n}} > 8.6 \times 10^{7}\ s$$

Baldoceolin et al

Zeit. fur. Phys. C 63 (1994)

There are proposals to improve this bound by two orders of magnitude at Deep Underground Science and Engineering Laboratory in South Dakota (DUSEL).

- When a bound neutron in the nucleus changes into an $\overline{n}$ the latter annihilates with another nucleon in the same nucleus:

$$
\begin{aligned}
(A, Z) \rightarrow (A-1, Z, \overline{n}) & \\
& \rightarrow \quad (A-2, Z) + \pi' s
\end{aligned}
$$

Thus the $n - \overline{n}$ annihilation may be detected via the reactions

$$
\begin{aligned}
\overline{n} + n & \rightarrow \pi' s \rightarrow \mu' s \\
\overline{n} + p & \rightarrow \pi' s \rightarrow \mu' s
\end{aligned}
$$

Experiments such as:

Kamiokande: Water Cerncov detector

Soudan II : Iron detector

- The difficulty with such a method is the fact the (potential) energy difference ΔE is very large due to nuclear potential:

$$\Delta E \simeq (100 - 500)\ MeV$$

$\Rightarrow$ the oscillations are strongly suppressed
for example for $\delta m \sim 10^{-22}\ eV$ (which corresponds to $\tau_{n\bar{n}} \sim 10^{6}\ s$), the amplitude of the oscillations is

$$A_{n\bar{n}} = \frac{\delta m}{\sqrt{\delta m^2 + \Delta E^2}} \sim \frac{\delta m}{\Delta E} \sim 10^{-19}$$

For $\Delta E t \gg 1$, the average probability of finding $\bar{n}$ is

$$P_{n\bar{n}} = \frac{1}{2}\left(\frac{\delta m}{\Delta E}\right)^2$$

which gives an annihilation rate which is constant in time

$$T_{n\bar{n}}^{-1} \sim \delta m^2$$

$$\Rightarrow \tau_{n\bar{n}} = \sqrt{T_R T_{n\bar{n}}}$$

T_R : typical period in nuclear physics ($\sim 10^{-23}\ s$)
$\Rightarrow$ the measurement of nuclear stability makes it in principle possible to determine $\tau_{n\bar{n}}$

However there are uncertainties that arise from the fact that T_R must be determined by nuclear structure calculations.
e.g:

$$T_R(^{16}O) = (1.7 - 2.6) \times 10^{-23}\ s$$
$$T_R(^{56}Fe) = (2.2 - 3.4) \times 10^{-23}\ s$$

No annihilation event have been detected:

- Kamiokande Collaboration gives $T_{n\bar{n}}(^{16}O) > 4.3 \times 10^{31}\ yrs$
  M. Takita et al
  Phys. ReV. D 34 (1986)

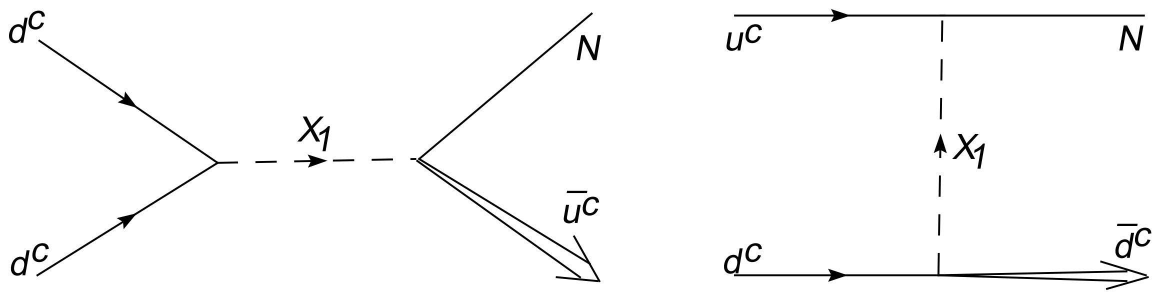
$$\rightarrow (\tau_{n\bar{n}})_{KM} > (0.7 - 0.8) \times 10^8\ s$$

- Frejus Collaboration gives $T_{n\bar{n}}(^{56}Fe) > 7 \times 10^{31}\ yrs$
  Ch. Berger et al
  Phys. Lett. B 240 (1990)

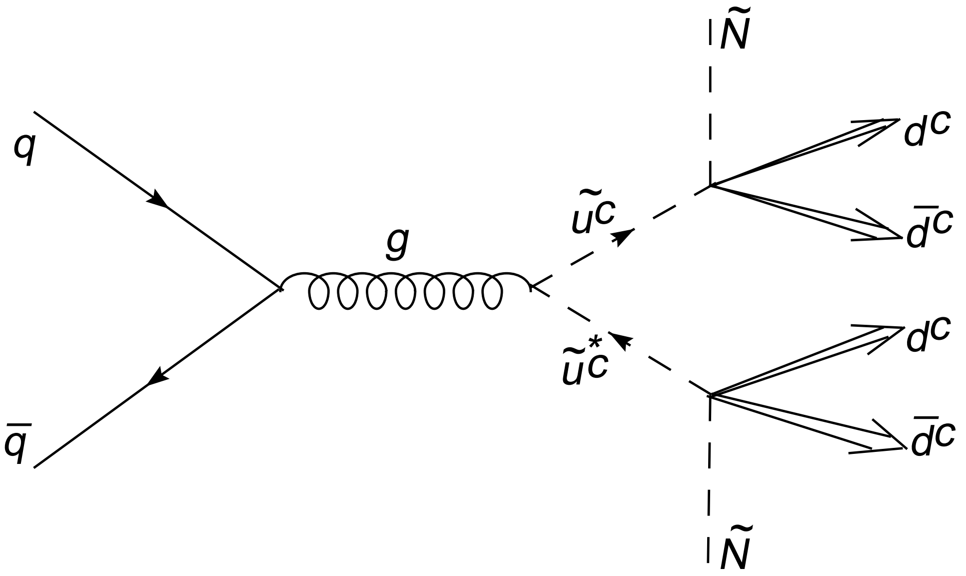
$$\rightarrow (\tau_{n\bar{n}})_{Soudan} > (0.8 - 1) \times 10^8\ s$$

Signature at LHC

• Monojet + missing energy signals from X production in pp collision:



• 4 jets + missing energy from :



Conclusion

- A simple extension of the MSSM that gives a unified TeV picture of DM and BAU
- Less fine tuned than the MSSM
- Collider (e.g LHC) different from the MSSM
- Neutron-antineutron transition time in the observable range