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# Neutron→ Antineutron Oscillations

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# What motivates searches for baryon instability?

- Baryon asymmetry of the universe (BAU).
  *Sakharov (1967), Kuzmin (1970)* **...**

- In Standard Model baryon number is not conserved (at the non-perturbative level).
  *'t Hooft (1976)* **...**

- Idea of Unification of particles and their interactions.
  *Pati & Salam (1973): quark– lepton unification, Left - Right symmetry* **…**
  *Georgi & Glashow (1974): SU(5) - unification of forces* **...**

- New low quantum gravity scale models.
  *N. Arkani-Hamed, S. Dimopoulos, G. Dvali (1998)* **...**

# Three ingredients needed for BAU explanation

*(A. Sakharov, 1967, V. Kuzmin 1970)*

**(1) Baryon number violation**

**(2) C and CP symmetry violation**

**(3) Departure from thermal equilibrium**

# In “Standard Model”

Baryon and Lepton numbers are violated at non-perturbative level.

*‘t Hooft (1976)*

This fact must be very important for the Early Universe when temperature was above 100 GeV, however at the present low temperatures this effect is so small that doesn’t lead to any observable consequences.

In nucleon disappearance the conservation of angular momentum requires that spin ½ of nucleon should be transferred to another fermion (either lepton or another nucleon):

> That leads to the selection rule:
>
> $\Delta B = \pm\,\Delta L$ or $|\Delta(B-L)| = 0, 2$

- In Standard Model always $\Delta(B-L) = 0$
- Second possibility of $|\Delta(B-L)| = 2$ allows transitions:
  $\Delta B = -\,\Delta L$, $|\Delta B| = 2$, and $|\Delta L| = 2$

***Conservation or violation of (B–L) is an essential issue in the discussion of baryon instability.***

# First Unification Models:

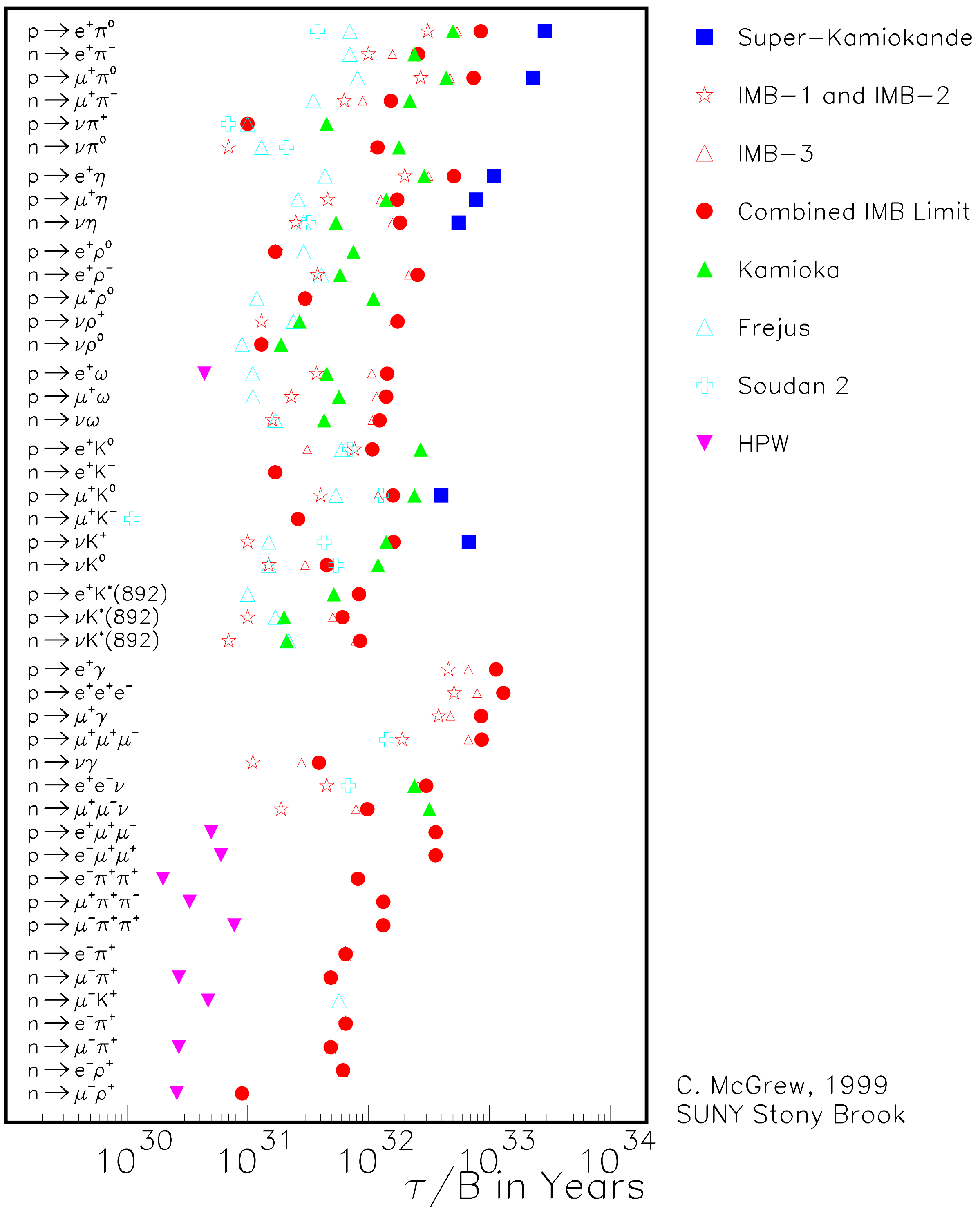
## in 1973 J. Pati and A. Salam: $SU(2)_L \otimes SU(2)_R \otimes SU(4)_C$

- Quark-lepton unification through SU(4) color
- Restoration of Left-Right symmetry (broken in SM)
- Violation of Baryon and Lepton number
- Quantization of Electric Charge
- Existence of Right-Handed neutrinos
- (B−L) as a Local Gauge Symmetry
- Violation of (B−L): $N \to$ lepton + X, $\nu \leftrightarrow \bar{\nu}$, and $n \leftrightarrow \bar{n}$ oscillations

## in 1974 H. Georgi and S. Glashow: SU(5)

- Quark-lepton unification
- Violation of Baryon and Lepton number
- Quantization of Electric Charge
- Prediction of the proton decay $p \to e^+ + \pi^0$ with lifetime $10^{31\pm1}$ years
- Neutrino masses = 0, no Right-Handed neutrinos
- Grand Unification of forces (e-m, weak, and strong) at $E \sim 10^{14}$ GeV
- Prediction of $\sin^2\vartheta_W = 0.214 \pm 0.004$
- Prediction of Great Desert between $\sim 10^3$ and $\sim 10^{14}$ GeV
- Global conservation of (B−L)

# Nucleon Lifetime Limits




http //superk.physics.sunysb.edu/ mcgrew/pdk limits.ps

*As a result of extensive experimental p-decay searches in the past ~20 years a number of (B–L) conserving models have been rejected:*

- ⊗ **Original SU(5)**
- ⊗ **One-step-broken SO(10)**
- ⊗ **SUSY extended SU(5)**
- ⃠ **SUSY extended SO(10)**

***It is time to look for the processes with Δ(B–L) = 2!***

# Is (B–L) quantum number conserved?

- In our laboratory samples (protons + neutrons – electrons):

$$(B-L) \neq 0$$

- However, in the Universe most of the leptons exist as, yet undetected, relict $\nu$ and $\bar{\nu}$ radiation (similar to CMBR) and conservation of (B–L) on the scale of the whole Universe in an open question;

- From the Equivalence Principle tests *(Eötvös, 1922; Dickey et al., 1964; Braginsky & Panov, 1972)* "(B–L) photons" *(Sakharov, 1988)* can be excluded at the level of $\sim 10^{-12}$, i.e. it is very unlikely that (B–L) is a good local symmetry.

- Non-conservation of (B–L) was discussed since 1978 by: *Davidson, Marshak, Mohapatra, Wilczek, Chang, Ramond, ...)*

# Is (B–L) violated?

As theoretically discovered *in 1985 by Kuzmin, Rubakov, and Shaposhnikov*, the non-perturbative effects of Standard Model (*sphalerons*) will wipe out BAU at electro-weak energy scale if BAU was generated at some unification scale > 1 TeV by (B–L) conserving processes. If (B–L) is violated at the scale above 1 TeV, BAU will survive.

Violation of (B–L) implies nucleon instability modes:

$$n \to \bar{n},\ p \to \nu\nu e^{+},\ n \to \nu\nu\bar{\nu},\ etc. \text{ or } \Delta(\text{B–L}) = -2$$

rather than conventional modes:

$$p \to e^{+}\pi^{0},\ p \to \bar{\nu}K,\ p \to \mu^{+}K^{0},\ etc. \text{ or } \Delta(\text{B–L}) = 0$$

If conventional (B–L) conserving proton decay would be discovered tomorrow by Super-K, it will not help us to understand BAU.

# Physics of (B–L) violation scale should include:

$$|\Delta(B-L)|=2$$

(1) $N \to l + X$ and $N \to ll\bar{l} + X$

(2) Majorana masses of ν's

(3) Neutrinoless double β-decay

(4) Intranuclear *NN* disappearance

(5) Vacuum $n \to \bar{n}$ transitions

# Neutron $\rightarrow$ Antineutron Transition

- The oscillation of neutral matter into antimatter is well known to occur in $K^0 \rightarrow \overline{K}^0$ and $B^0 \rightarrow \overline{B}^0$ particle transitions due to the non-conservation of *strangeness* and *beauty* quantum numbers by electro-weak interactions.

- There are no laws of nature that would forbid the $n \rightarrow \bar{n}$ transitions except the conservation of "*baryon charge (number)*":

*M. Gell-Mann and A. Pais, Phys. Rev.* ***97*** *(1955) 1387*
*L. Okun, Weak Interaction of Elementary Particles, Moscow, 1963*

- First suggested as a possible BAU mechanism by

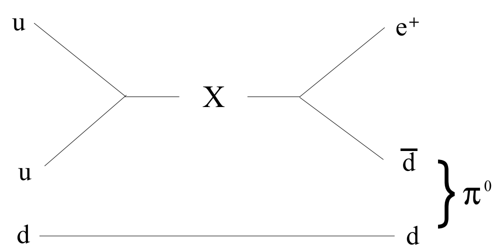
*M. V. Kuzmin, 1970*

- First considered and developed within the framework of Unification models by

*R. Mohapatra and R. Marshak, 1979*

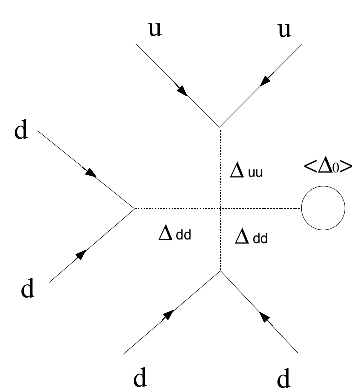
# Energy scale of $n \rightarrow \bar{n}$ transitions is intermediate between SM and GUT

- Most favorable in SU(5) $p \rightarrow e^+\pi^0$ decay is due to X- & Y- bosons (with masses ~ $10^{15}$ GeV) exchange with amplitude ~ $m^{-2}$ (for dimensional reasons) :




$$M_p \sim \frac{g^2}{m_X^2}$$

- in the lowest order the $n\bar{n}$-transition should involve 6-quark operator with the amplitude (again for dimensional reasons) ~ $m^{-5}$:




$$M_{n\bar{n}} \sim \frac{1}{m_{\aleph}^5}$$

Observable $n \rightarrow \bar{n}$ transition rates would correspond to the mass scale $m_{\aleph}$ ~ $\mathbf{10^5}$ GeV

# Recent important theoretical papers on $n \to \bar{n}$

- K.S. Babu and R.N. Mohapatra, “Observable neutron-antineutron oscillations in seesaw models of neutrino mass”, Physics Letters B 518 (2001) 269-275

- S. Nussinov and R. Shrock, “N-nbar Oscillations in Models with Large Extra Dimensions”, hep-ph/0112337 v1 27 Dec 2001

- G. Dvali and G. Gabadadze, “Non-conservation of global charges in the Brane Universe and baryogenesis”, Physics Letters B 460 (1999) 47-57

# Probability of neutron-antineutron transition

$$\Psi(t)=\begin{pmatrix}\Psi_n(t)\\ \Psi_{\bar{n}}(t)\end{pmatrix}=a_n(t)\begin{pmatrix}1\\0\end{pmatrix}+a_{\bar{n}}(t)\begin{pmatrix}0\\1\end{pmatrix}$$

where $\Psi(0)=\begin{pmatrix}1\\0\end{pmatrix}$; $\quad a_n(0)=1;\ a_{\bar{n}}(0)=0$

$|\Psi|^2=a_n^2+a_{\bar{n}}^2=1$ — normalization.

Evolution of antineutron component vs time can be found from time-dependent Schrödinger equation:

$$i\hbar\frac{\partial\Psi}{\partial t}=\hat{H}\Psi$$

with Hamiltonian of the system:

$$\hat{H}=\begin{pmatrix}E_n & \alpha\\ \alpha & E_{\bar{n}}\end{pmatrix}$$

where $E_n, E_{\bar{n}}$ are non-relativistic energy operators

$$E_n=m_n+\frac{p^2}{2m_n}+V_n\ ;\ E_{\bar{n}}=m_{\bar{n}}+\frac{p^2}{2m_{\bar{n}}}+V_{\bar{n}}$$

- We assume CPT and $\rightarrow m_n = m_{\bar{n}} = m$
- We assume that the gravity is the same for $n$ and $\bar{n}$
- In practical case (Earth magnetic field) $V_n = -V_{\bar{n}} = V$;

  $V_n = \vec{\mu} \cdot \vec{B}$ and $V_{\bar{n}} = -\vec{\mu} \cdot \vec{B}$ $(\vec{\mu} = \vec{\mu}_n = -\vec{\mu}_{\bar{n}})$ and

$$\hat{H} = \begin{pmatrix} m+V & \alpha \\ \alpha & m-V \end{pmatrix}$$

$$P_{n \rightarrow \bar{n}}(t) = \frac{1}{2} \cdot \frac{\alpha^2}{\alpha^2 + V^2} \cdot (1 - \cos\omega t); \quad \omega = \frac{2 \cdot \sqrt{\alpha^2 + V^2}}{\hbar}$$

external fields different for neutrons and antineutrons can suppress transition !

if external fields are small (vacuum transition) and $\omega t \ll 1$:

$$P_{n \rightarrow \bar{n}}(t) \approx \frac{\alpha^2}{\hbar^2} \cdot t^2 = \left( \frac{t}{\tau_{n\bar{n}}} \right)^2$$

where $\tau_{n\bar{n}} = \frac{\hbar}{\alpha}$ or $\alpha = \frac{\hbar}{\tau_{n\bar{n}}}$;

where $\tau_{n\bar{n}}$ – characteristic transition time

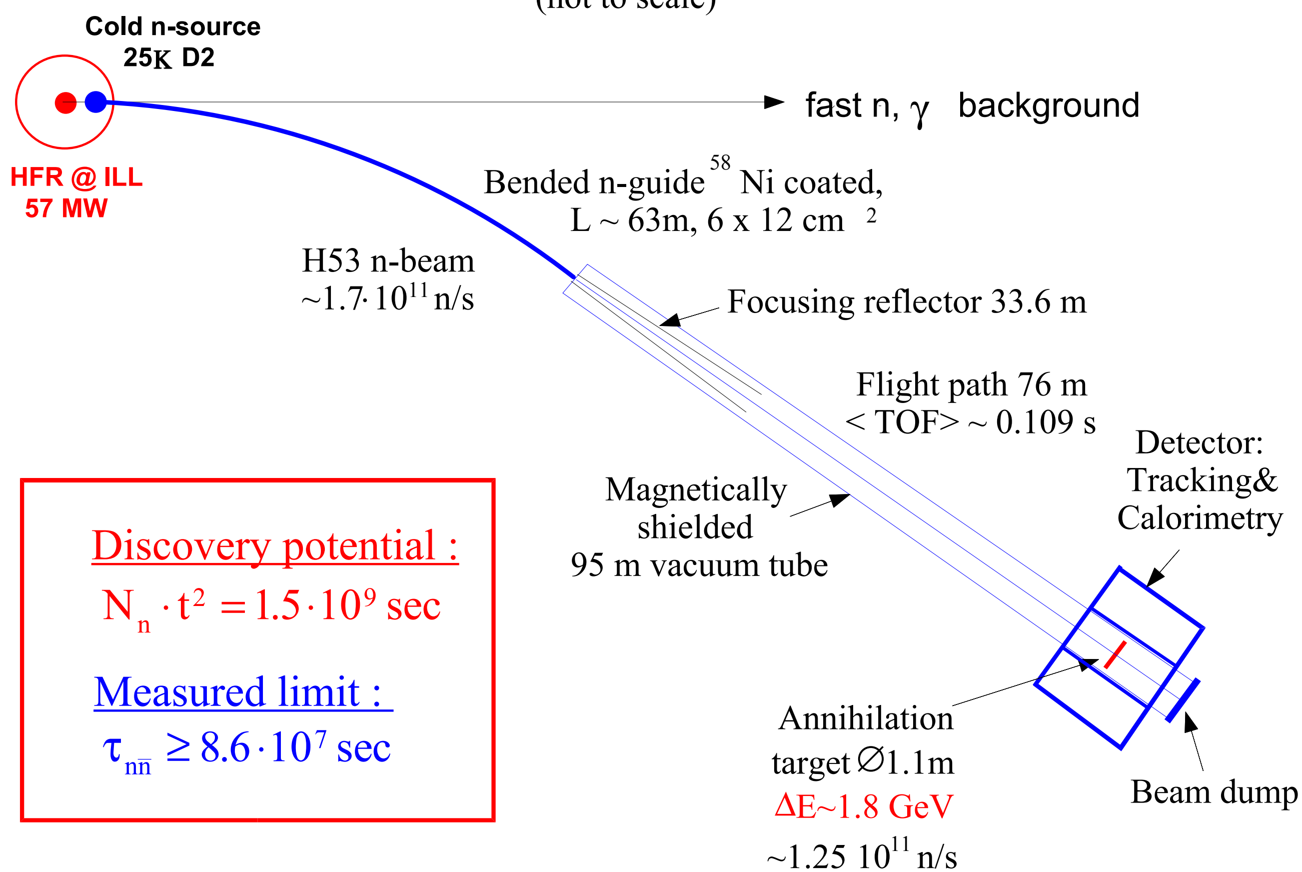
All dynamics of $n \rightarrow \bar{n}$ transition is determined by $\alpha$

**Discovery potential (sensitivity) $\Rightarrow$ D.P. $\sim N_n \cdot \langle t^2 \rangle$**

where $N_n$ – number of neutrons/s on a detector
and $\sqrt{\langle t^2 \rangle}$ – average neutron flight time

# Schematic layout of Heidelberg - ILL - Padova - Pavia $n\bar{n}$ search experiment at Grenoble 89-91

(not to scale)

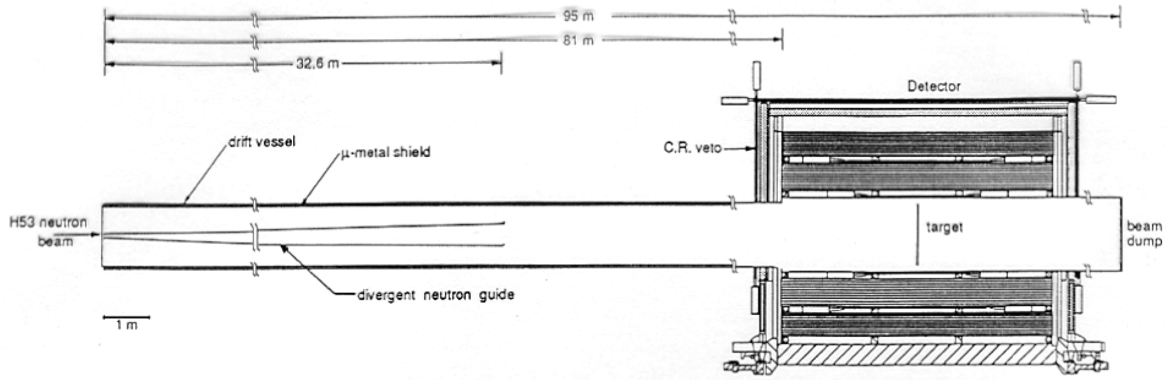



Discovery potential :

$$N_n \cdot t^2 = 1.5 \cdot 10^9 \text{ sec}$$

Measured limit :

$$\tau_{n\bar{n}} \geq 8.6 \cdot 10^7 \text{ sec}$$

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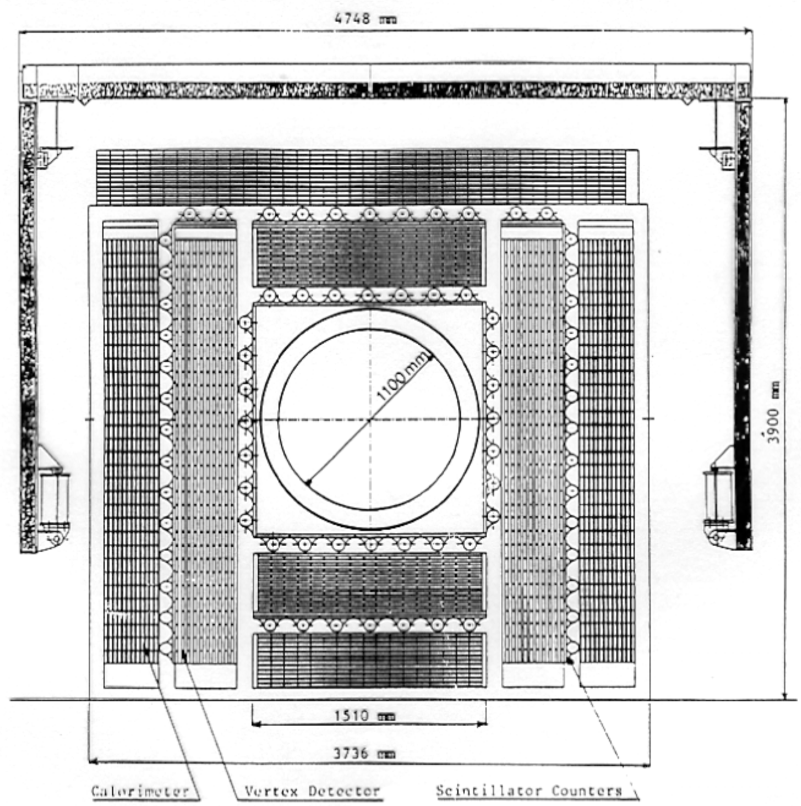



b

Fig. 1. (a) Experimental apparatus showing the "quasi free" neutron propagation length with the divergent guide, the target and the detection system. (b) Cross sectional view of the detector.

# Detector of Heidelberg-ILL-Padova-Pavia Experiment

# Suppression of $n \to \bar{n}$ in intranuclear transitions

(simple picture by V. Kuzmin)

Neutrons inside nuclei are "free" for the time:

$$\Delta t \sim \frac{1}{E_{binding}} \sim \frac{1}{10\text{MeV}} \sim 10^{-22}\text{s}$$

and "experience" this condition N times per second:

$$N \sim \frac{1}{\Delta t}$$

Transition probability per second:

$$P_{nucl} = \frac{1}{\tau_{nucl}} = \left(\frac{\Delta t}{\tau_{n\bar{n}}}\right) \cdot \left(\frac{1}{\Delta t}\right) \text{ and}$$

$$\boxed{\tau_{nucl} = \frac{\tau_{n\bar{n}}^2}{\Delta t} = T_R \cdot \tau_{n\bar{n}}^2}$$

$$T_R \sim \frac{1}{\Delta t} \sim 10^{22} \text{ s}^{-1}$$ - "nuclear suppression factor"

# Intranuclear neutron → antineutron transitions:

| | | |
|---|---|---|
| Soudan II'2002 | $\tau_A \geq 7.2 \cdot 10^{31}$ | years (Fe) |
| IMB'84 | $\tau_A \geq 2.4 \cdot 10^{31}$ | years ($O_2$) |
| KAMIOKANDE'86 : | $\tau_A \geq 4.3 \cdot 10^{31}$ | years ($O_2$) |
| FRÉJUS'90: | $\tau_A \geq 6.5 \cdot 10^{31}$ | years (Fe) |
| Expected Super-K (optimistically): | $\tau_A \geq 1 \cdot 10^{33}$ | years ($O_2$) |

Experimental signature of $n \to \bar{n}$ is <5> π's

For vacuum transitions of free neutrons: M. Baldo-Ceolin et al., ZPHY C63 (1994) 409 at ILL/Grenoble reactor: $\tau_{free} > 8.6 \cdot 10^7$ sec

**Intranuclear transitions are heavily suppressed:**

$$\tau_A = R \cdot \tau_{free}^2$$

**where R is "nuclear suppression factor" $\sim 10^{23}$ $s^{-1}$**

Theoretical progress on R during the last ~ 20 years was due to the works of: V. Kuzmin et al.; R. Mohapatra and R. Marshak, C. Dover, A. Gal, and J. M. Richard; P. Kabir; W. Alberico et al.; and most recently J. Hüfner and B. Kopeliovich ⇒

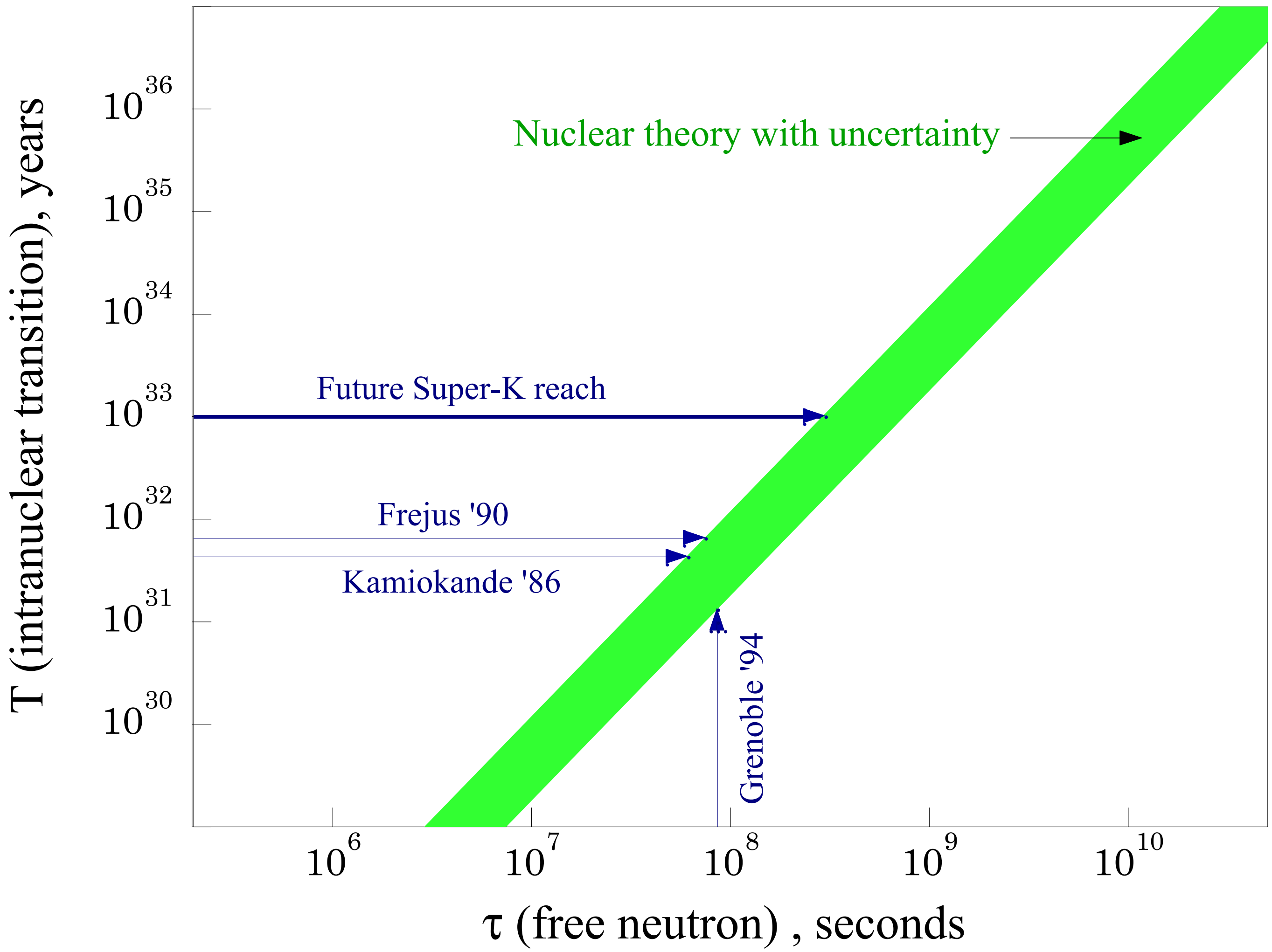
| | |
|---|---|
| $^{16}O$: | $R=(1.7\text{-}2.6)\cdot 10^{23}$ $s^{-1}$ |
| $^{56}Fe$: | $R=(2.2\text{-}3.4)\cdot 10^{23}$ $s^{-1}$ |
| $^{40}Ar$: | $R=(2.1\text{-}3.2)\cdot 10^{23}$ $s^{-1}$ |
| $^{2}D$: | $R=2.5\cdot 10^{22}$ $s^{-1}$ |

Present PDG limit: $\tau_{free}(\text{intranuclear}) \geq 1.2 \cdot 10^8$ s

Expected Super-K result: $4 \cdot 10^8$ s

# Present Neutron-Antineutron transition limits

$T_{intnuc} = R * (\tau_{free})^2$, where R is "nuclear suppression factor" in intranuclear transitio

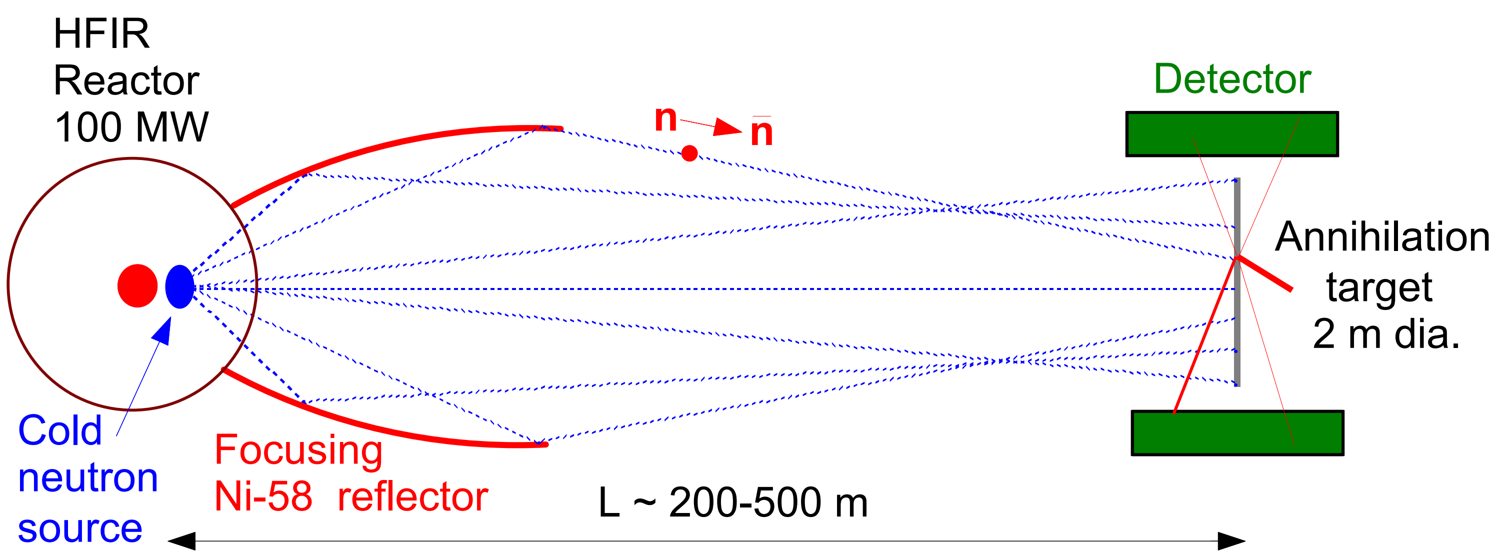


# $n \rightarrow \bar{n}$ Search Sensitivity

Fréjus limit ≈ Grenoble limit = 1 unit (1 u) of sensitivity

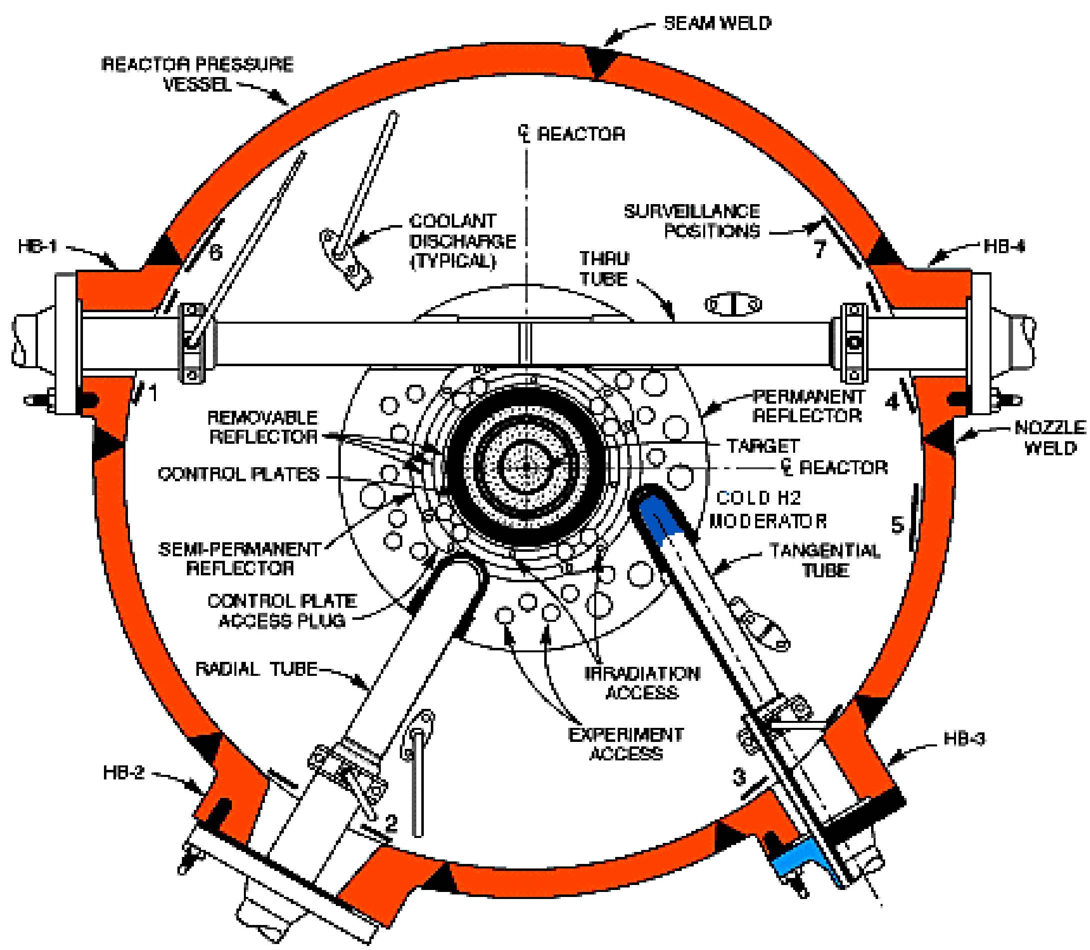
| Method | Present limit | Possible future limit | Possible sensitivity increase |
|---|---|---|---|
| Intranuclear (in N-decay expts) | $6.5 \cdot 10^{31}$ yr = 1u (Fréjus) | $10^{33}$ yr (Super-K) | × 16 u |
| UCN trap | none | $\sim 5 \cdot 10^{8}$ s (PSI)<br>$\sim 1 \cdot 10^{9}$ s (ESS) | × 30 u<br>× 150 u |
| Geo-chemical (ORNL) | none | $4 \cdot 10^{8} \div 1 \cdot 10^{9}$ s (Tc in Sn ore) | × 15÷150 u |
| Cold reactor beam | $8.6 \cdot 10^{7}$ s = 1u (@ILL/Grenoble) | $3 \cdot 10^{9}$ s (@HFIR/ORNL) | × 1,000 u |

# New advanced layout for HFIR/ORNL




Conceptual layout of $n \to \bar{n}$ search experiment
for HFIR/ORNL reactor with focusing reflector (not to scale)

High-Flux Isotope Reactor at Oak Ridge National Laboratory




Section view of ORNL/HFIR reactor. For $n \rightarrow \bar{n}$ search experiment the cold supercritical hydrogen moderator should be installed in the HB–3 beam tube.

# Comparison

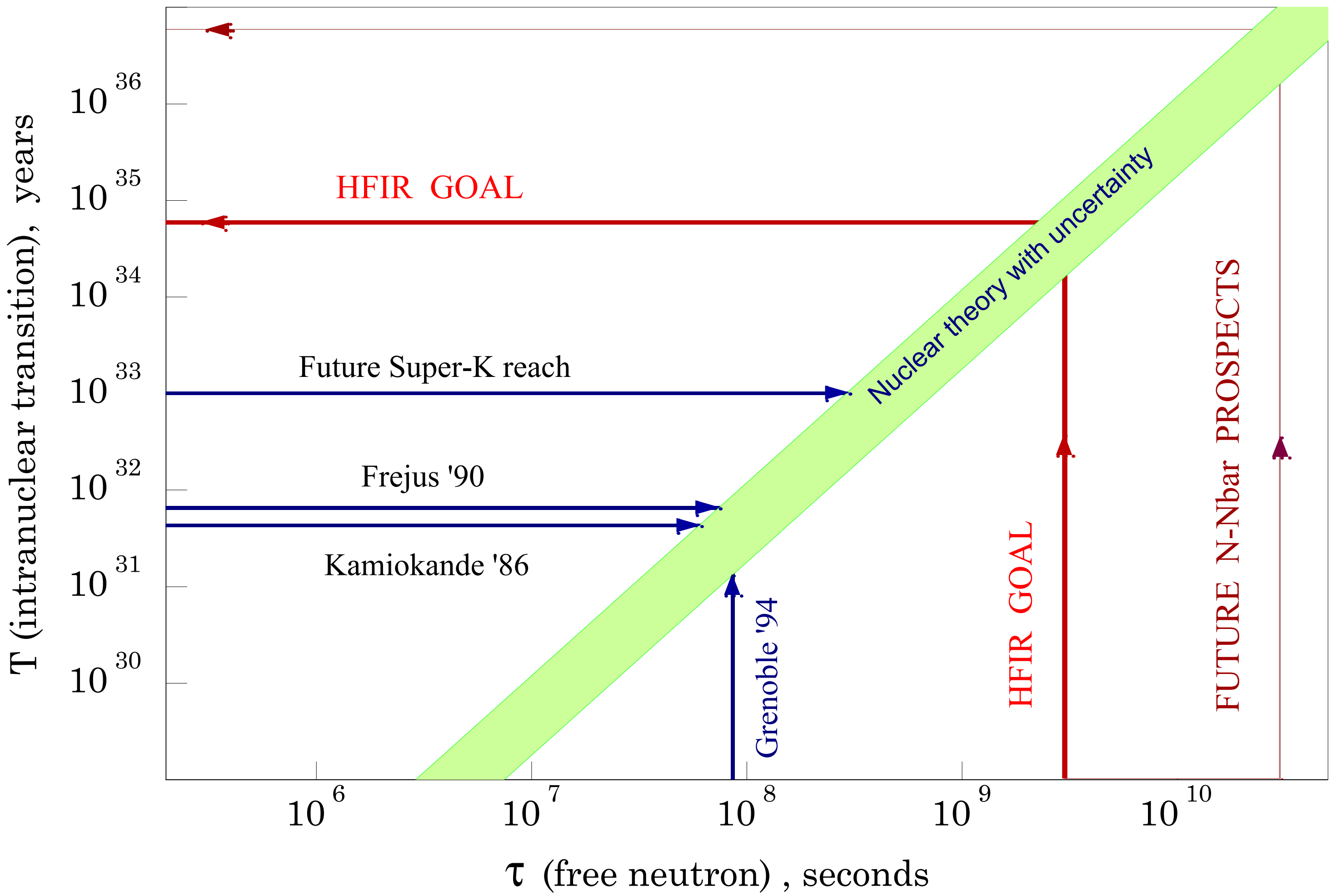
***of the major parameters of the new $n \to \bar{n}$ search experiment proposed for HFIR HB–3 beam at ORNL with another recent reactor-based experiment.***

| Neutron source | RHF/Grenoble | HFIR/Oak Ridge (HB–3 beam) |
|---|---|---|
| Reference | M. Baldo-Ceolin et al., Z. Phys. C63 (1994) 409 | W. Bugg et. al, LOI UTK-PHYS-96-L1 |
| Status | Completed experiment | Proposal |
| Reactor power (MW) | 58 | (85) 100 |
| Reactor's peak thermal n-flux | $1.4 \cdot 10^{15}$ (n/cm$^2$/s) | $1.5 \cdot 10^{15}$ (n/cm$^2$/s) |
| Moderator | Liquid $D_2$ | Supercritical $H_2$ |
| Source area | 6×12 cm$^2$ | ~ 11 cm dia. |
| Target diameter | 1.1 m | 2.0 m |
| Flight path | 76 m | 300 m |
| Neutron fluence @ target | $1.25 \cdot 10^{11}$ n/s | ~ $8.5 \cdot 10^{12}$ n/s |
| Average time of flight | 0.109 s | 0.271 s |
| Detector efficiency | 0.48 | ~ 0.5 |
| Operation time (s) | $2.4 \cdot 10^7$ | $7 \cdot 10^7$ (~3 years) |
| $\tau_{n\bar{n}}$ limit (90% CL) | $8.6 \cdot 10^7$ s | $3.0 \cdot 10^9$ s |
| Discovery potential per second | $1.5 \cdot 10^9$ n·s$^2$ | $6.2 \cdot 10^{11}$ n·s$^2$ |
| **Sensitivity** | **1** | **~ 400** |

For *one day* of operation at HFIR in a new proposed n-nbar search one can obtain the same Discovery Potential *as* for *one year* of the previous RHF-based experiment in Grenoble.

# Stability of matter from Neutron-Antineutron transition search

$T_{intnuc} = R * (\tau_{free})^2$ , where R is "nuclear suppression factor" in intranuclear transitions



# CPT test ($m = \overline{m}$?) in $n \rightarrow \bar{n}$ transitions

(if the latter would be observed)

*[Abov, Djeparov, Okun, JETP Lett, **39** (1984)493]*

$$i\hbar \frac{\partial \Psi}{\partial t} = \hat{H}\Psi, \text{ where } \hat{H} = \begin{pmatrix} m_n & \alpha \\ \alpha & m_{\bar{n}} \end{pmatrix}$$

$\Delta m = m_{\bar{n}} - m_n$; assuming no external fields

$$P = \frac{\alpha^2}{\alpha^2 + (\Delta m/2)^2} \cdot \sin^2\left[\frac{\sqrt{\alpha^2 + (\Delta m/2)^2}}{\hbar} \cdot t_{obs}\right]$$

$$\text{where} \quad t_{obs} < \frac{\hbar}{\Delta m}$$

If $\alpha \neq 0$, then $n \rightarrow \bar{n}$ transition exists. If then $\Delta m$ would be larger than $\sim 1/t_{obs}$, the $n \rightarrow \bar{n}$ transition of free neutrons in vacuum will be suppressed, but the intranuclear $n \rightarrow \bar{n}$ transitions will not be suppressed significantly more than they are by the difference of intranuclear potential for neutron and anti-neutron.

| Δm/m experimentally known as: | |
|---|---|
| $9 \pm 5 \cdot 10^{-5}$ | for neutrons |
| $< 8 \cdot 10^{-9}$ | for $e^+$ and $e^-$ |
| $1.5 \pm 1.1 \cdot 10^{-9}$ | for protons |
| $< 10^{-18}$ | for $K^0$s |

With $n \rightarrow \bar{n}$ transitions the CPT symmetry can be tested down to $\Delta m/m \sim 10^{-23}$, i.e. below the $m_n/m_{Plank} \cong 10^{-19}$.

# Importance of $n \rightarrow \bar{n}$ search

## *If discovered:*

- $n \rightarrow \bar{n}$ will establish a new force of nature and a new phenomenon leading to the physics at the energy scale of ~$10^5$ GeV.
- Will provide an essential contribution to the understanding of baryon asymmetry of the universe.
- New physics emerging from the models with low quantum gravity scale can be revealed.
- New symmetry principles determining the history of the universe during the 1st second of creation can be established: $\Delta(B-L) \neq 0$.
- Further experiments with free reactor neutrons + underground experiments will allow testing with unprecedented sensitivity:

– whether $m_n = m_{\bar{n}}$ (CPT theorem) with $\Delta m/m \approx 10^{-23}$

– gravitational equivalence of baryonic matter and antimatter

## *If NOT discovered:*

- Within the reach of 1,000 times improved experimental sensitivity a new limit on the stability of matter at the level of ~ $10^{35}$ years will be established.
- Wide class of SUSY-based models will be removed *(K. Babu and R. Mohapatra, 2001).*

# Conclusions

Thinking of 2000's is different from 1980's:

| **1980's** | **2000's** |
|---|---|
| • GUT models conserving (B–L) were popular for BAU | • BAU not at GUT scale; Δ(B–L)≠0 is needed for BAU |
| • No indications for neutrino mass | • $m_\nu \neq 0$ and Majorana nature of neutrino |
| • Great Desert from SUSY scale to GUT scale | • Possible unification with gravity at ~ $10^5$ GeV scale |
| ► $p \to e^+\pi^0,\ p \to \bar{\nu}K^+$, *etc.* | ► $n \to \bar{n},\ \nu_R,\ 2\beta 0\nu,\ n \to 3\nu$, *etc.* |

→ *Future searches for baryon instability should look for* $n \to \bar{n}$ *and* $B\text{–}L$ *violation in both reactor and underground experiment*