

Neutron \rightarrow Antineutron Transition Search

Introduction and Overview

Yuri A. Kamyshkov

*Department of Physics
University of Tennessee, Knoxville, TN*

kamyshkov@utk.edu

What motivates searches for baryon instability?

- Baryon asymmetry of the universe (BAU).
Sakharov (1967), Kuzmin (1970) ...
- 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 ...
- In Standard Model baryon number is not conserved (at the non-perturbative level).
't Hooft (1976) ...
- 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

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
- Left-Right symmetry and restoration of Parity Conservation 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
- Possible violation of $(B-L)$: $N \rightarrow \text{lepton} + X$, $\nu \leftrightarrow \bar{\nu}$, 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 $p \rightarrow e^+ + \pi^0$ with lifetime $10^{31 \pm 1}$ 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 existence of Great Desert between $\sim 10^3$ and $\sim 10^{14}$ GeV
- Conservation of $(B-L)$

Searches for baryon instability

- So far searches for baryon instability were focused mainly on the (B–L) conserving processes, i.e. $\Delta(B-L)=0$, motivated by GUT and SUSY–GUT schemes with unification scale of $\sim 10^{15}-10^{16}$ GeV.

$$N \rightarrow \text{anti-lepton} + X:$$

$$p \rightarrow e^+ \pi^0 ; p \rightarrow \bar{\nu} K^+ ; p \rightarrow \mu^+ K^0 \text{ etc.}$$

- Pioneering experimental searches by IMB, Kamiokande, Fréjus, and later Soudan-II and Super-K pushed the limits for some exclusive nucleon decay modes to the impressive $\geq 10^{33}$ years. New experiments (UNO or Hyper-K) can expand these limits by another factor of 10–20.
- *No nucleon decay was found so far, thus, ruling out the original SU(5) Unification model where (B–L) is conserved.*

Is (B–L) quantum number conserved?

- Our laboratory samples (protons + neutrons – electrons) have
 $(B-L) > 0$
- However, in the Universe most of the leptons exist as, yet undetected, relict ν 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. conservation of (B–L) is two orders of magnitude “less probable” than conservation of Baryon charge.
- 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:

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

rather than conventional modes:

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

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) $N \rightarrow l + X$ and $N \rightarrow ll\bar{l} + X$
- (2) Majorana masses of ν 's
- (3) Neutrinoless double β -decay
- (4) Intranuclear NN disappearance
- (5) Vacuum $n \rightarrow \bar{n}$ transitions

Neutron \rightarrow Antineutron Transition

- The oscillation of neutral matter into antimatter is well known to occur in $K^0 \rightarrow \bar{K}^0$ and $B^0 \rightarrow \bar{B}^0$ 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

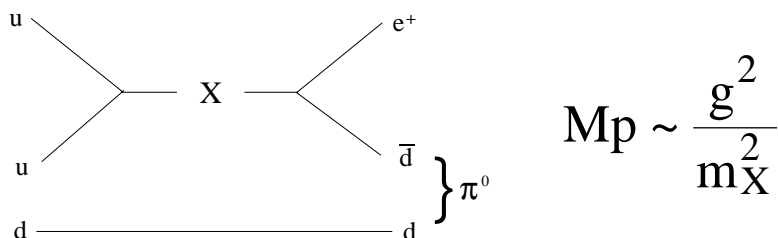
M. V. Kuzmin, 1970

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

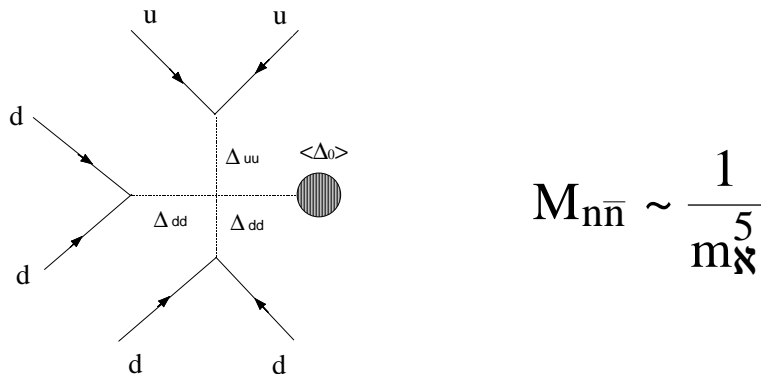
R. Mohapatra and R. Marshak, 1979

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 $\sim 10^{15}$ GeV) exchange with amplitude $\sim m^{-2}$ (for dimensional reasons) :



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



Observable $n \rightarrow \bar{n}$ transition rates would correspond to the mass scale $m_X \sim 10^5 - 10^6$ GeV

In the models with low quantum gravity scale

$n \rightarrow \bar{n}$ can occur, for example, due to brane fluctuations

[G. Dvali et al., Phys. Lett. B460: 47-57,1999]

The Standard Model particles are localized on the brane, which is a fluctuating object. Due to quantum fluctuations brane gets curved locally and creates a bubble ("baby brane") which detaches from the brane and goes into extra dimension where it effectively becomes a black hole, then it reenters again on the brane and decays there. This baby brane can take away any particle with strictly zero gauge charge such as neutron and return back any other combination of the same mass, and quantum numbers such as spin etc., for instance, anti-neutron. On the brane this process will be seen as $n \rightarrow \bar{n}$ transition.

The same process cannot lead to the proton decay, since the charged particles cannot leave the brane, because the photon is localized there.

[See also other ideas by: R. Mohapatra et al., Phys.Lett.B491:143-147,2000;

C. E. Carlson and C. D. Carone, hep-ph/0103180]

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

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

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

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

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

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

- 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 $\omega t \ll 1$:

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

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

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

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

Discovery potential \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

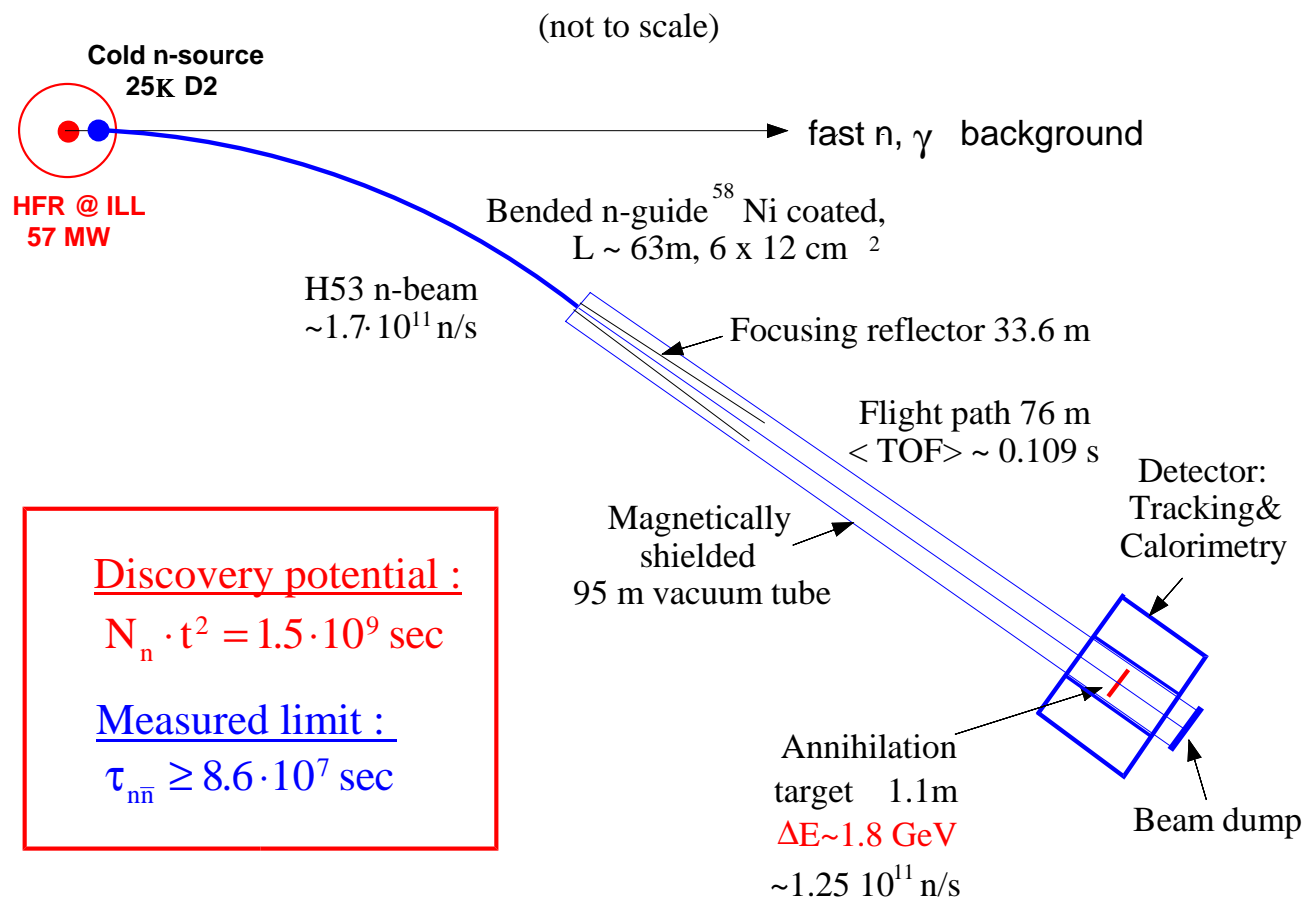
n \rightarrow \bar{n} transition search

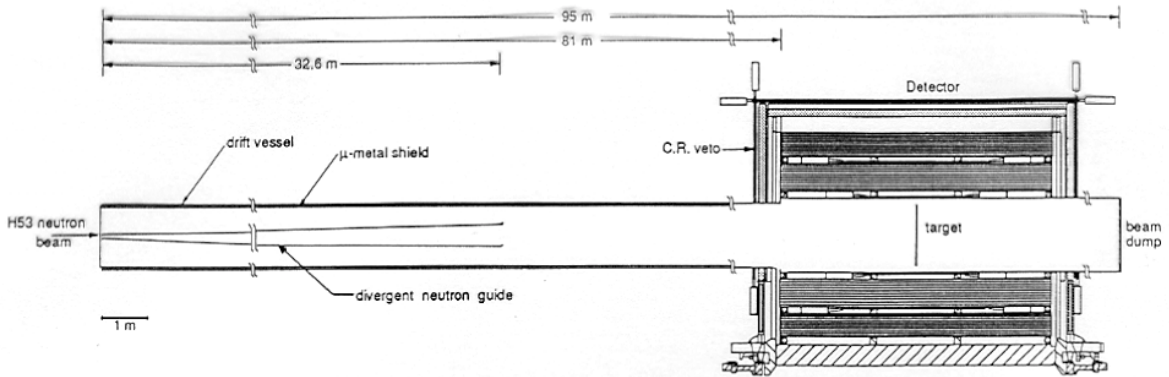
experiments with free neutrons

~1975 (expt.)	LUSCHIKOV...	@JINR	$\tau_{n\bar{n}} > 1 \cdot 10^3 \text{ s}$
1980 (proposal)	FIDECARO...	@ILL	\rightarrow
1982 (proposal)	GOODMAN... (Harvard-ORNL-UT)	@ORR	(not approved)
1983 (proposal)	ILYINOV... (INR/Moscow Meson Factory)	@INR	(approved, now stalled)
1985 (published)	FIDECARO...	@ILL	$\tau_{n\bar{n}} > 1 \cdot 10^6 \text{ s}$
~1986 (proposal)	BALDO-CEOLIN...	@ILL	\rightarrow
1990 (first result)	BALDO-CEOLIN...	@ILL	$\tau_{n\bar{n}} > 1 \cdot 10^7 \text{ s}$
1994 (published)	BALDO-CEOLIN...	@ILL	$\tau_{n\bar{n}} > 8.6 \cdot 10^7 \text{ s}$

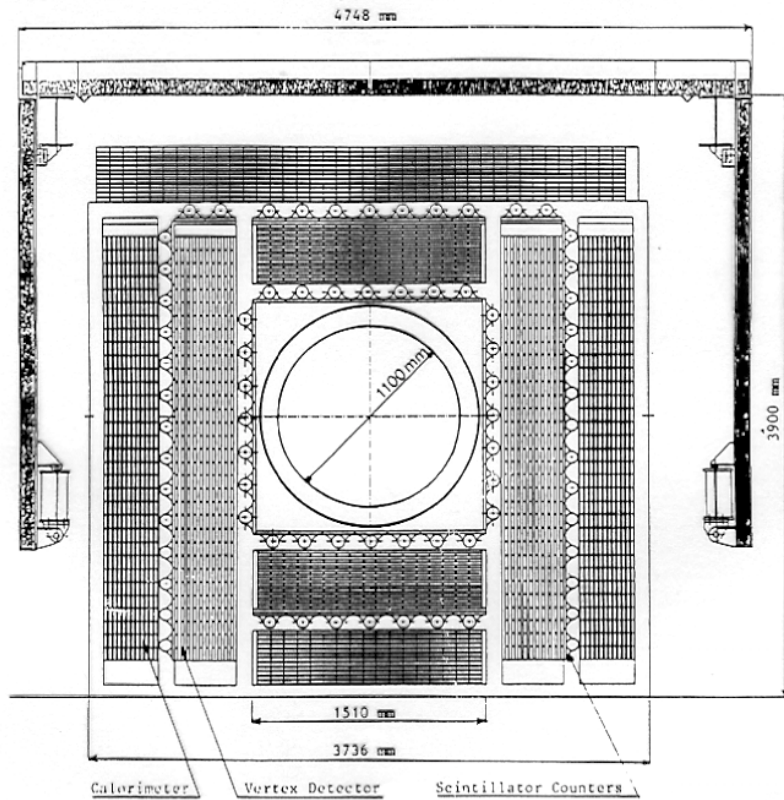
For 9 years (from 1985 to 1994) the experimental limit
on free $n\bar{n}$ oscillations time has been improved
from $\tau_{n\bar{n}} > 1 \cdot 10^6 \text{ s}$ to $\tau_{n\bar{n}} > 8.6 \cdot 10^7 \text{ s}$
or the discovery potential was increased by factor $7.4 \cdot 10^3$

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





a



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

Intranuclear neutron \rightarrow antineutron transitions:

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)
Super-K (by \sim 2004):	$\tau_A \geq 1.6 \cdot 10^{33}$ years (O_2) ?

Experimental signature of $n \rightarrow \bar{n}$ is $\langle 5 \rangle \pi$'s

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

Intranuclear transitions are heavily suppressed:

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

where R is “nuclear suppression factor” $\sim 10^{23} \text{ s}^{-1}$

Theoretical progress on **R** during the last \sim 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 \Rightarrow

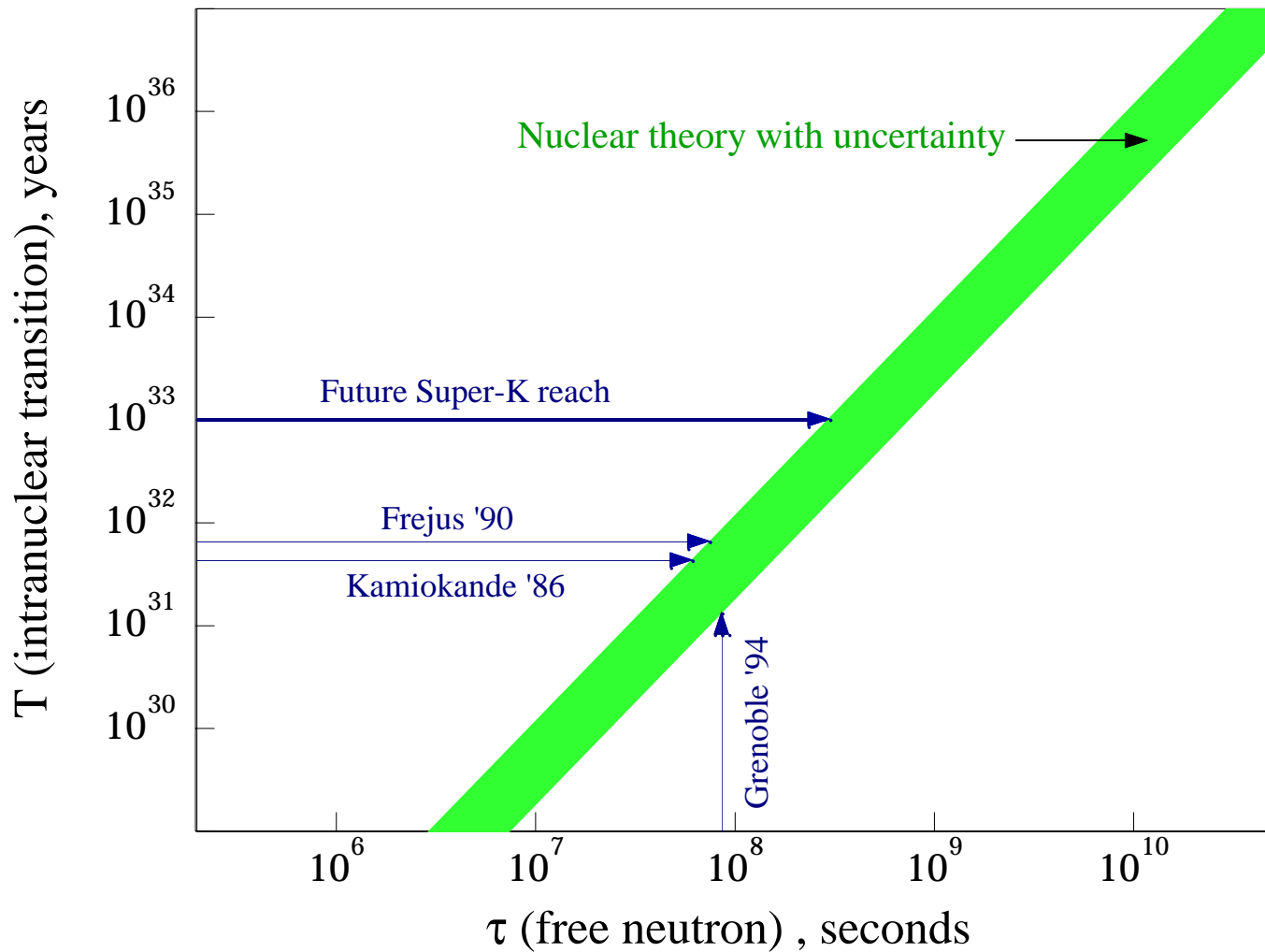
^{16}O :	$R=(1.7-2.6) \cdot 10^{23} \text{ s}^{-1}$
^{56}Fe :	$R=(2.2-3.4) \cdot 10^{23} \text{ s}^{-1}$
^{40}Ar :	$R=(2.1-3.2) \cdot 10^{23} \text{ s}^{-1}$
^{12}C :	Not yet treated

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

Super-K by year \sim 2004: $\tau_{\text{free}} \geq 5 \cdot 10^8 \text{ s}$

Present Neutron-Antineutron transition limits

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



CPT test ($m = \bar{m}$?) 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

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

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

If $\alpha \neq 0$, then $n \rightarrow \bar{n}$ transition exists. If then Δm 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.

$\Delta m/m$ 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 $m_n/m_{\text{Plank}} \cong 10^{-19}$.

Conclusions

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

1980's	2000's
<ul style="list-style-type: none">• GUT models conserving (B-L) were popular for BAU	<ul style="list-style-type: none">• No need for GUT; $\Delta(B-L) \neq 0$ is needed for BAU
<ul style="list-style-type: none">• No indications for neutrino mass	<ul style="list-style-type: none">• $m_\nu \neq 0$ and Majorana nature of neutrino
<ul style="list-style-type: none">• Great Desert from SUSY scale to GUT scale	<ul style="list-style-type: none">• Possible unification with gravity at $\sim 10^5$ GeV scale
<ul style="list-style-type: none">▶ $p \rightarrow e^+ \pi^0, p \rightarrow \bar{\nu} K^+, etc.$	<ul style="list-style-type: none">▶ $n \rightarrow \bar{n}, \nu_R, 2\beta 0\nu, n \rightarrow 3\nu, etc.$

Reflecting these changes, future experimental programs should include experimental searches for $n \rightarrow \bar{n}$