Searches for Baryon Instability Other than Proton Decay

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Plan to discuss:

- Mode independent nucleon decay
- Neutron disappearance in KamLAND
- Search for (B–L) violation
- Neutron $\rightarrow$ Antineutron transition search

Physics Seminar at IPNS
KEK *November 26, 2002*

What motivates searches for baryon instability?

Need for explanation of the observed baryon asymmetry of the Universe (BAU)

A. Sakharov (1967): three ingredients needed for BAU explanation:

(1) Baryon number violation
(2) C and CP symmetry violation
(3) Departure from thermal equilibrium

BAU does not give us a priori mode of nucleons decay.
Particular decay modes are predictions of theoretical models.

- In Standard Model baryon number is not conserved *'t Hooft (1976)* ...
  (important in early Universe, but not observable at low temperatures. Alone can not explain BAU).
- Idea of Unification of particles and their interactions.
  Pati & Salam (1973): quark– lepton unification …
  Georgi & Glashow (1974): SU(5) - unification of forces ...
- New low quantum gravity scale models.
  N. Arkani-Hamed, S. Dimopoulos, G. Dvali (1998) ...

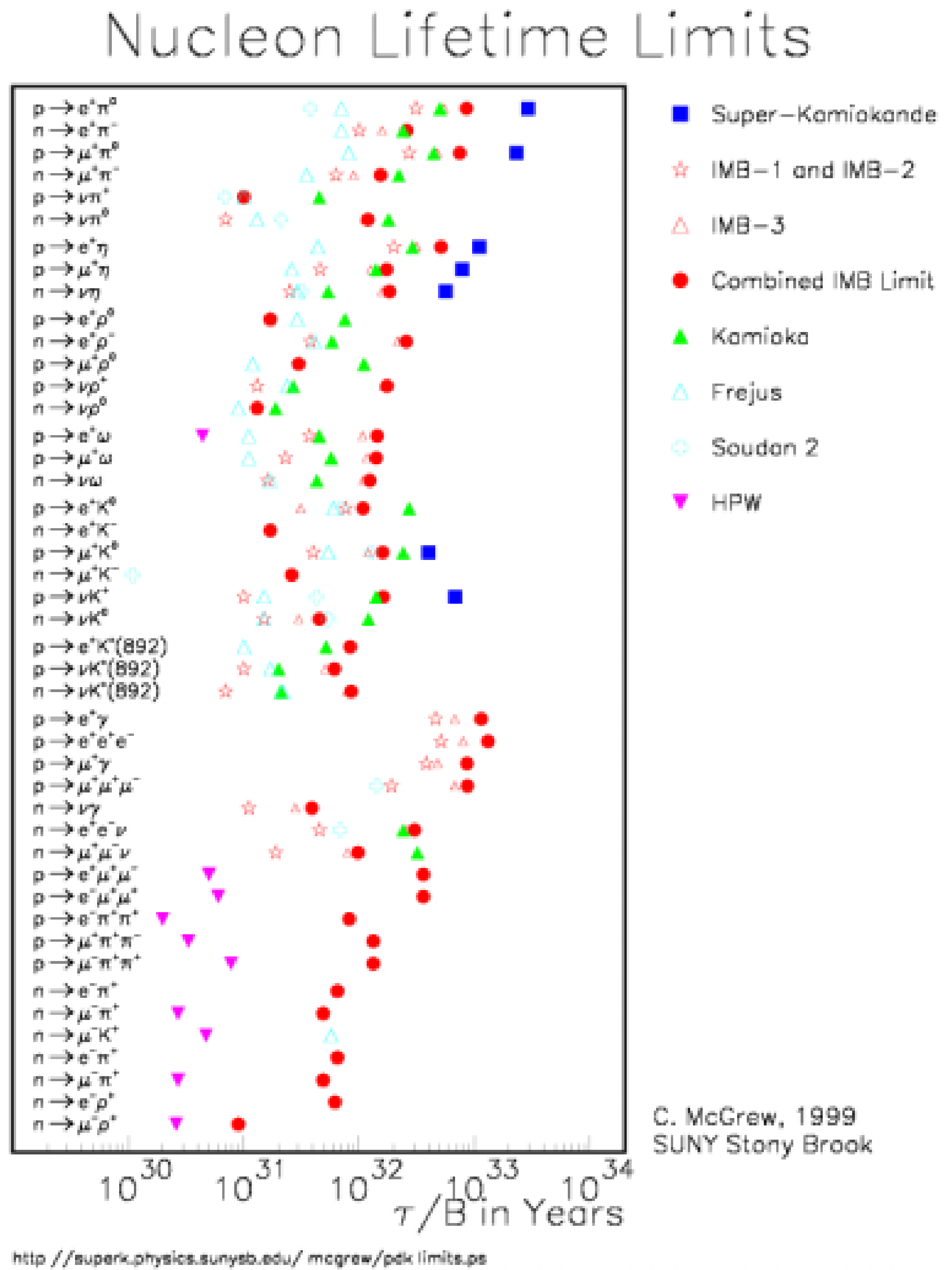
Results of > 20 years of nucleon decay searches by Kamiokande, IMB, Super-K, Frejus, Soudan-2…

Impressive limits reached (S-K):

$$p \rightarrow e^{+}\pi^{0} > 5.7 \times 10^{33}\ years$$

$$p \rightarrow \bar{\nu}\ K^{+} > 2.0 \times 10^{33}\ years$$

Did we explore all the possibilities? What can we say about nucleon lifetime?



Mode-independent limit for nucleon lifetime is only

> 1.6×10^{25} years !

Citation: K. Hagiwara *et al.* (Particle Data Group), Phys. Rev. D **66**, 010001 (2002) (URL: http://pdg.lbl.gov)

p MEAN LIFE

A test of baryon conservation. See the "p Partial Mean Lives" section below for limits that depend on decay modes. p = proton, n = bound neutron.

LIMIT (years)	*PARTICLE*	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
>1.6×10^{25}	***p, n***		[22,23] EVANS 77		
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>4×10^{23}	p	95	TRETYAK 01		$d \to n + ?$
>1.9×10^{24}	p	90	[24] BERNABEI 00B	DAMA	
>3×10^{23}	p		[23] DIX 70	CNTR	
>3×10^{23}	p, n		[23,25] FLEROV 58		

[22] Mean lifetime of nucleons in ^{130}Te nuclei.
[23] Converted to mean life by dividing half-life by ln(2) = 0.693.
[24] BERNABEI 00B looks for the decay of a $^{128}_{53}$I nucleus following the disappearance of a proton in the otherwise-stable $^{129}_{54}$Xe nucleus. The p decay is to neutrinos or to "nothing," and thus doesn't conserve charge as well as baryon number.
[25] Mean lifetime of nucleons in ^{232}Th nuclei.

$\overline{p}$ MEAN LIFE

Of the two astrophysical limits here, that of GEER 00D involves considerably more refinements in its modeling. The other limits come from direct observations of stored antiprotons. See also "$\overline{p}$ Partial Mean Lives" after "p Partial Mean Lives," below, for exclusive-mode limits. The best (lifetime/branching fraction) limit there is 7×10^{5} years, for $\overline{p} \to e^- \gamma$. We advance only the exclusive-mode limits to our Summary Tables.

LIMIT (years)	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>8×10^{5}	90		[26] GEER 00D		$\overline{p}/p$ ratio, cosmic rays
>0.28			GABRIELSE 90	TRAP	Penning trap
>0.08	90	1	BELL 79	CNTR	Storage ring
>1×10^{7}			GOLDEN 79	SPEC	$\overline{p}/p$ ratio, cosmic rays
>3.7×10^{-3}			BREGMAN 78	CNTR	Storage ring

[26] GEER 00D uses agreement between a model of galactic $\overline{p}$ production and propagation and the observed $\overline{p}/p$ cosmic-ray spectrum to set this limit.

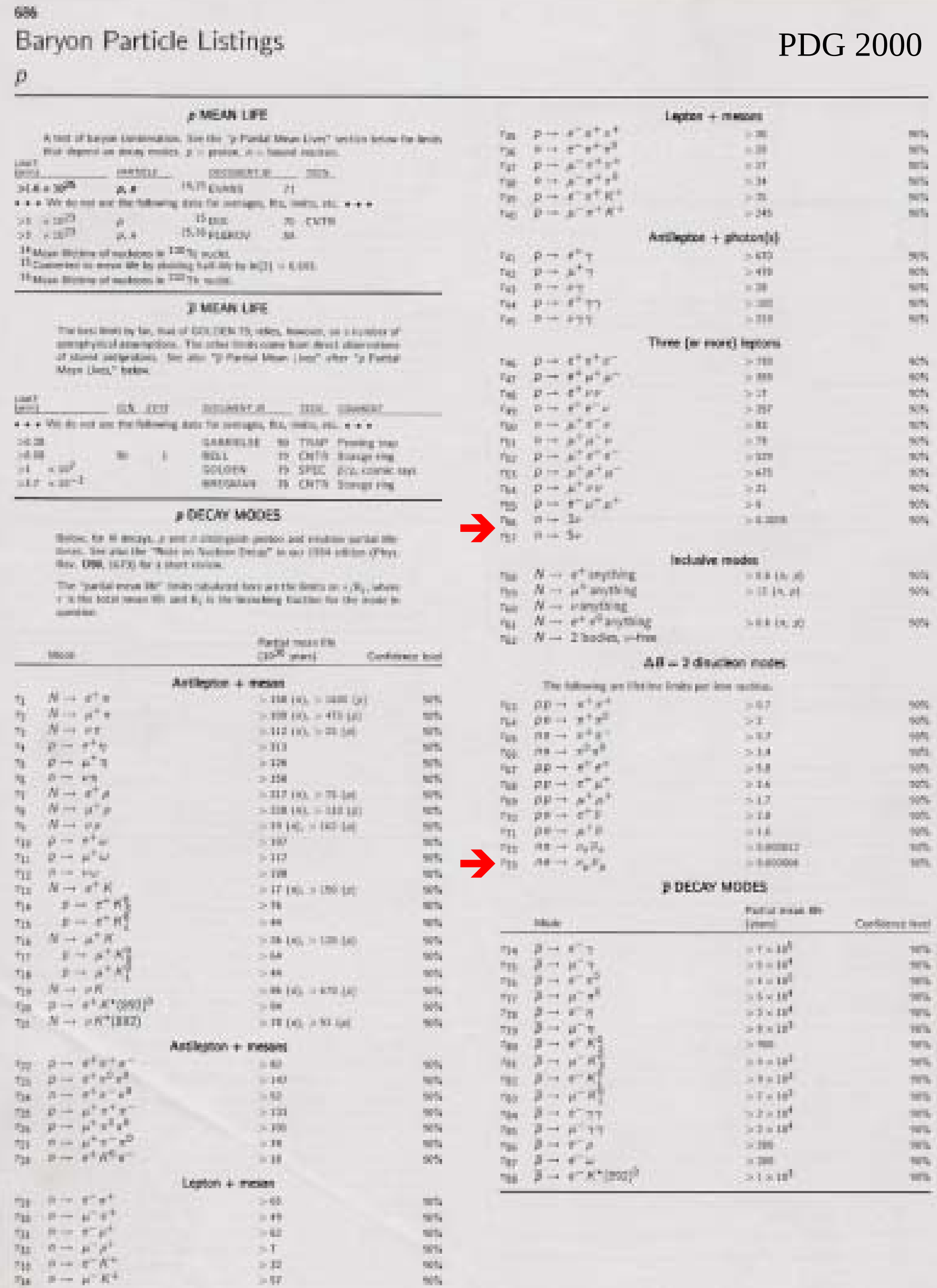
Most of measured modes have lifetime > $n \cdot 10^{30}$ years

but few exceptions:

$n \to 3\nu$	$> 5 \times 10^{26}$	years
$nn \to \nu_e \bar{\nu}_e$	$> 1.2 \times 10^{25}$	years
$nn \to \nu_\mu \bar{\nu}_\mu$	$> 6 \times 10^{24}$	years

$pp \to K^+ K^+$	**not measured**
$nn \to K^0 K^0$	**not measured**

PDG 2000



What is "Mode-independent nucleon lifetime"?

$\tau > 1.6 \cdot 10^{25}$ years

by J.C. Evans and R.I. Steinberg, Science, Vol. 197 (1977) 989-991
based on the paper of E.W. Hennecke et al., Phys Rev C11(1975) 1378-1384

where Xe isotopes extracted from dated $2.46 \cdot 10^{9}$ years old 3.791 g telluride ore from Kalgoorlie lodes in Western Australia were analyzed.

$$^{130}\mathrm{Te}\ (\mathrm{n\ decay}) \rightarrow {}^{129}\mathrm{Te} \rightarrow \beta \rightarrow {}^{129}\mathrm{Xe}$$

$$^{130}\mathrm{Te}\ (\mathrm{p\ decay}) \rightarrow {}^{129}\mathrm{Sb} \rightarrow \beta \rightarrow {}^{129}\mathrm{Xe}$$

advantage: accumulation of potential signal for ~ 10^{9} years

Science 197 (1977) 989	Xe content ($\times 10^{-13}$ cm^3 STP g^{-1})		
Isotope	Total	Atmosphere component	Net excess
Xe - 128	0.63	0.34	0.29
Xe - 129	11.0	4.63	6.37
Xe - 130	509.7	0.72	509.0
Xe - 131	6.27	3.71	2.56
Xe - 132	4.71	4.71	0.0

Let's use only conservation laws:

(energy-momentum, angular momentum, electric charge)

Neutrons can decay:

①	to charged particles + hadrons	(well measured)
②	to invisible particles (ν)	(not well measured!)
③	or disappear to unknown channels	(not well measured!)

Protons can decay:

①	to charged particles + hadrons	(well measured)
②	to invisible particles (ν)	(not possible!)
③	or disappear to unknown channels	(not possible!)

• Evans and Steinberg in the mode-independent lifetime limit addressed essentially ② + ③. Some of modes ① would experience intranuclear final state interactions and can destroy residual daughter nucleus (^{129}Xe), but all these dangerous modes already had life-time limits above the mode-independent one.

• Super-K and future “proton decay” experiments are mostly focused on ① type of decays.

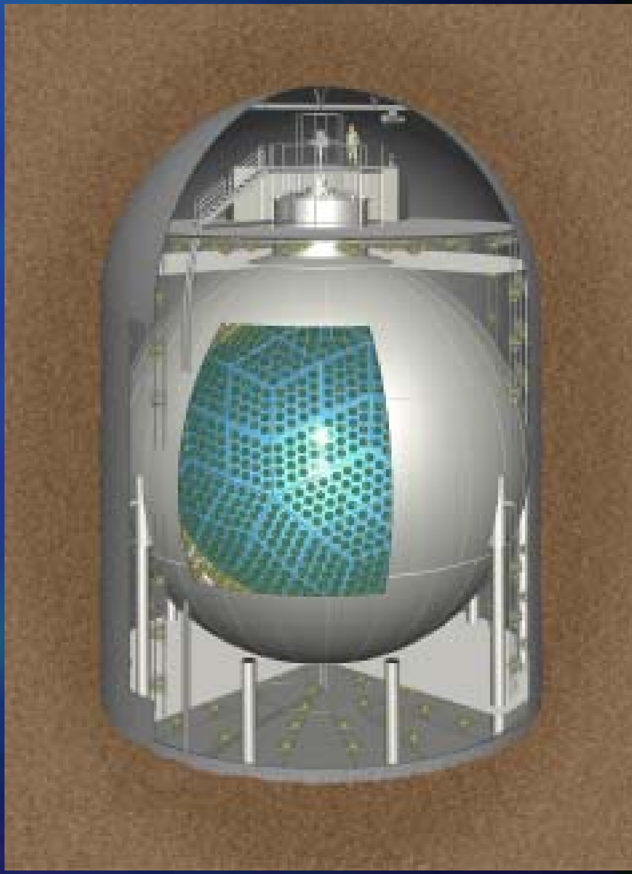
• Before exploring further type ① modes of decay one should measure all what was *not well measured*. Corresponding mode-independent lifetime limits should be and can be improved up to the level of other modes 10^{30}–10^{31} years.

• On this way one can either discover nucleon instability or establish a new (mode-independent) limit on the stability of matter.

Neutron disappearance can be searched in KamLAND

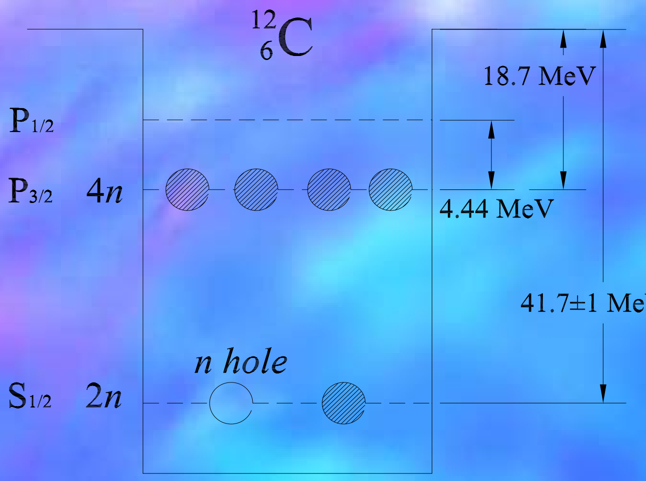
$n \to \nu\nu\bar{\nu}, \quad nn \to \nu\bar{\nu}$ ② *and also* ③

Unique features of KamLAND detector:



- Large mass: 1,000 ton of Liquid Scintillator (~ CH_2)
- Low detection threshold: < 1 MeV
- Good energy resolution: $\sim 7.5\% / \sqrt{E(MeV)}$
- Position reconstruction accuracy in x,y,z: ~ 25 cm
- Low background: 2700 mwe; buffer shield; veto-shield; Rn shield; LS purification for U, Th $< 10^{-16}$ g/g

These features allow observation of the sequence of nuclear de-excitation states produces by disappearance of nucleon.



Disappearance of neutron from ^{12}C will result in nuclear de-excitations of $^{11}C^*$

De-excitation of $^{11}C^*$ state produced by disappearance of a $S_{1/2}$ neutron in $^{12}C_6$

(Excitation level 23 MeV, width 7 MeV)

De-excitation branchings in %					
					only γ's 2.68
n + gs 2.97	n + γ 2.79	n + n 0.06	n + p 5.57	n + α 2.17	n + X 13.56
p + gs 2.86	p + γ 18.59	p + n 1.38	p + p 7.00	p + α 33.24	p + X 63.07
α + gs 5.09	α + γ 4.15	α + n 0.29	α + p 3.36	α + α 7.80	α + X 20.69

Branching $^{11}C^* \rightarrow {}^{10}C + n + \gamma$ = **2.79 ± 0.2 %** per $S_{1/2}$ neutron

E. Kolbe & Y.K. nucl-th / 0206030

Possible detection of $n \to 3\nu$ in KamLAND

$^{12}C(n \to 3\nu)^{11}C^*$

⇘ **n** + $^{10}C^*$

⇘ γ + ^{10}C (3.35 MeV γ)

⇘ $^{10}B + \beta^+$ (27 sec, Q_{EC} = 3.65 MeV, 99%)

3-hit signature: γ (3.35 MeV), **n** (~ 200 μs, 2.2 MeV), β^+ (27 sec, 2–3.65 MeV)

Rate of $n \to 3\nu$ events @ Limit		
Limit $\tau(n \to 3\nu)$	From	KamLAND events/kt/year
Present limit (90% CL) > $5 \cdot 10^{26}$ yr	PDG' 98	~ 5,000
Possible limit (90% CL) > $3.0 \cdot 10^{30}$ yr	KamLAND by 2005	Background < 1 event/year

- *Search limit for one neutron disappearance **($n \to 3\nu$)** can be improved in KamLAND by 3-4 orders of magnitude*
- *Similar improvements can be made for two-neutron disappearance*

(B–L) number

In nucleon disappearance the conservation of angular momentum requires that spin ½ of nucleon should be transferred to another fermion:

That leads to the selection rule:

$$\Delta B = \pm \Delta L \quad \text{or} \quad |\Delta(B-L)| = 0, 2$$

- 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 and search for baryon instability.

First Unification Models

First Unification Models:

$SU(2)_L \otimes SU(2)_R \otimes SU(4)_C \leftarrow SO(10)$

- Quark-lepton unification through SU(4) color *(J. Pati and A. Salam, 1973)*
- Restoration of Left-Right symmetry *(R. Mohapatra, J. Pati and G. Senjanovic)*
- Violation of Baryon and Lepton number
- Quantization of Electric Charge
- Existence of Right-Handed neutrinos
- (B–L) as a Local Gauge Symmetry *(R. Mohapatra, R. Marshak; A. Davidson)*
- Violation of (B–L): $N \rightarrow lepton + X$, $\nu \leftrightarrow \overline{\nu}$, $n \leftrightarrow \overline{n}$ *(R. Mohapatra, R. Marshak)*

$SU(5) \leftarrow SO(10)$

- Grand Unification of forces at E ~ 10^{14} GeV *(H. Georgi and S. Glashow, 1974)*
- 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 $10^{31\pm1}$ years
- Neutrino masses = 0, no Right-Handed neutrinos
- Prediction of $\sin^2\vartheta_W = 0.214 \pm 0.004$
- Prediction of Great Desert between ~ 10^3 and ~ 10^{14} GeV
- Global conservation of (B–L)

(B–L) in 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.

$$N \to \text{anti-lepton} + X: \quad p \to e^{+}\pi^{0}\ ;\ \ p \to \bar{\nu}K^{+}\ ;\ \ p \to \mu^{+}K^{0}\ \text{etc.}$$

- Pioneering experimental searches by IMB, Kamiokande, Fréjus, and later by Soudan-II and Super-K pushed the limits for some exclusive nucleon decay modes to the impressive $\geq 10^{33}$ years.

- *No nucleon decay was found so far, thus, ruling out:*

the original SU(5), one-step-broken SO(10), SUSY-extended SU(5), and almost excluding SUSY-extended SO(10) models.

In all these models (B–L) is conserved.

Is (B–L) quantum number conserved?

- In our laboratory samples (B–L) = #protons + #neutrons – #electrons:

$$\boxed{(B-L) \neq 0}$$

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

- Non-conservation of (B–L) was discussed theoretically 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 p-decay 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.

"The proton decay is not a prediction of the baryogenesis" T. Yanagida @ ν2002

Need for (B–L) violation search

- Questions whether (B–L) is violated in nature and how it is violated can be answered only by experiments!

- All that was not "well measured" in nucleon decay might violate (B–L). Processes with (B–L) violation should be an essential part of experimental baryon instability search program.

$$n \to \bar{n},\ n \to \nu\nu\bar{\nu},\ nn \to \nu\bar{\nu},\ p \to e^{+}\nu\nu, \ldots$$

- $n \to \bar{n}$ is a most promising direction of (B–L) violation search and BAU explanation.

- Observation of $n \to \bar{n}$ can be spectacular and unambiguous. Sensitivity for $n \to \bar{n}$ search can be considerably improved by the next generation of experiments

(with cold reactor neutrons ***, UCN **, underground *)

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Neutron → 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→Nbar transitions except the conservation of "*baryon charge (number)*":

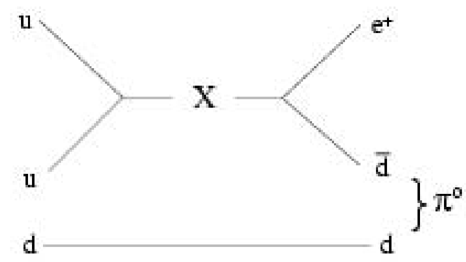
M. Gell-Mann and A. Pais, Phys. Rev. ***97*** *(1955) 1387*
L. Okun, Weak Interaction of Elementary Particles, Moscow, 1963

- First suggested as a possible BAU mechanism by *V. Kuzmin, 1970*

- First considered and developed within the framework of Unification models by *R. Mohapatra and R. Marshak, 1979*

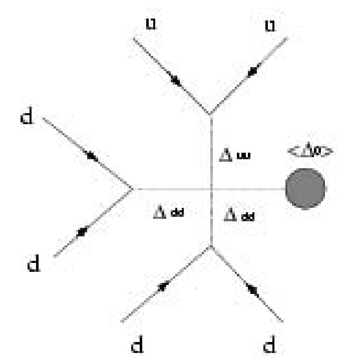
Energy scale of $n \rightarrow \bar{n}$ transitions is intermediate between SM and GUT

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



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

- In the lowest order the $n\bar{n}$-transition should involve 6-quark operator (dimension 9) with the amplitude (again for dimensional reason) ~ $m_{\aleph}^{-5}$:



$$M_{n\bar{n}} \sim \frac{g^2}{m_{\aleph}^5}$$

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

18 October 2001

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 518 (2001) 269–275

www.elsevier.com/locate/npe

Observable neutron–antineutron oscillations in seesaw models of neutrino mass

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Abstract

We show that in a large class of supersymmetric models with spontaneously broken $B-L$ symmetry, neutron–antineutron oscillations occur at an observable level even though the scale of $B-L$ breaking is very high, $v_{B-L} \sim 2 \times 10^{16}$ GeV, as suggested by gauge coupling unification and neutrino masses. We illustrate this phenomenon in the context of a recently proposed class of seesaw models that solves the strong CP problem and the SUSY phase problem using parity symmetry. We obtain an *upper* limit on $N-\bar{N}$ oscillation time in these models, $\tau_{N-\bar{N}} \leqslant 10^9$–$10^{10}$ s. This suggests that a modest improvement in the current limit on $\tau_{N-\bar{N}}$ of 0.86×10^8 s will either lead to the discovery of $N-\bar{N}$ oscillations, or will considerably restrict the allowed parameter space of an interesting class of neutrino mass models. © 2001 Published by Elsevier Science B.V.

←

Predicted n-nbar upper limit is within a reach of new reactor and UCN experiments

→

Quarks and leptons are separated by extra-dimension in this model: proton decay suppressed, n-nbar not since only quarks are involved

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n-$\bar{n}$ Oscillations in Models with Large Extra Dimensions

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We analyze n-$\bar{n}$ oscillations in generic models with large extra dimensions in which standard-model fields propagate and fermion wave functions have strong localization. We find that in these models n-$\bar{n}$ oscillations might occur at levels not too far below the current limit.

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5 August 1999

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 460 (1999) 47–57

Non-conservation of global charges in the Brane Universe and baryogenesis

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Proton decay is strongly suppressed in this model, but n-nbar is not since n_R has no gauge charges

Fig. 1. Creation of baby branes.

Fig. 2. Flux tube holding the baby brane with a local charge.

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

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

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

- 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) $V_n = -V_{\bar{n}} = V$;

$$V_n = \vec{\mu}\cdot\vec{B} \text{ and } V_{\bar{n}} = -\vec{\mu}\cdot\vec{B} \;\; (\vec{\mu} = \vec{\mu}_n = -\vec{\mu}_{\bar{n}}) \quad \text{and} \quad \hat{H} = \begin{pmatrix} m+V & \alpha \\ \alpha & m-V \end{pmatrix}$$

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

external fields different for neutrons and antineutrons will suppress transition !

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

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

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. ~ $N_n \cdot \langle t^2 \rangle$

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

PDG 2002:

Limits for both
free reactor neutrons and
neutron bound inside nucleus

Citation: K. Hagiwara *et al.* (Particle Data Group), Phys. Rev. D **66**, 010001 (2002) (URL: http://pdg.lbl.gov)

LIMIT ON $n\bar{n}$ OSCILLATIONS

Mean Time for $n\bar{n}$ Transition in Vacuum

A test of $\Delta B=2$ baryon number nonconservation. MOHAPATRA 80 and MOHAPATRA 89 discuss the theoretical motivations for looking for $n\bar{n}$ oscillations. DOVER 83 and DOVER 85 give phenomenological analyses. The best limits come from looking for the decay of neutrons bound in nuclei. However, these analyses require model-dependent corrections for nuclear effects. See KABIR 83, DOVER 89, ALBERICO 91, and GAL 00 for discussions. Direct searches for $n \to \bar{n}$ transitions using reactor neutrons are cleaner but give somewhat poorer limits. We include limits for both free and bound neutrons in the Summary Table.

VALUE (s)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$>8.6 \times 10^7$	90	BALDO-...	94	CNTR	Reactor (free) neutrons
$>1.2 \times 10^8$	90	BERGER	90	FREJ	n bound in iron
$>1.2 \times 10^8$	90	TAKITA	86	CNTR	n bound in oxygen
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$>1 \times 10^7$	90	BALDO-...	90	CNTR	See BALDO-CEOLIN 94
$>4.9 \times 10^5$	90	BRESSI	90	CNTR	Reactor neutrons
$>4.7 \times 10^5$	90	BRESSI	89	CNTR	See BRESSI 90
$>1 \times 10^6$	90	FIDECARO	85	CNTR	Reactor neutrons
$>8.8 \times 10^7$	90	PARK	85B	CNTR	
$>3 \times 10^7$		BATTISTONI	84	NUSX	
$> 2.7 \times 10^7 - 1.1 \times 10^8$		JONES	84	CNTR	
$>2 \times 10^7$		CHERRY	83	CNTR	

$> 6.5 \cdot 10^{31}$ **years** → (Fréjus)

Soudan II result from 2002

τ (Fe) $> 7.2 \cdot 10^{31}$ years (Fe)

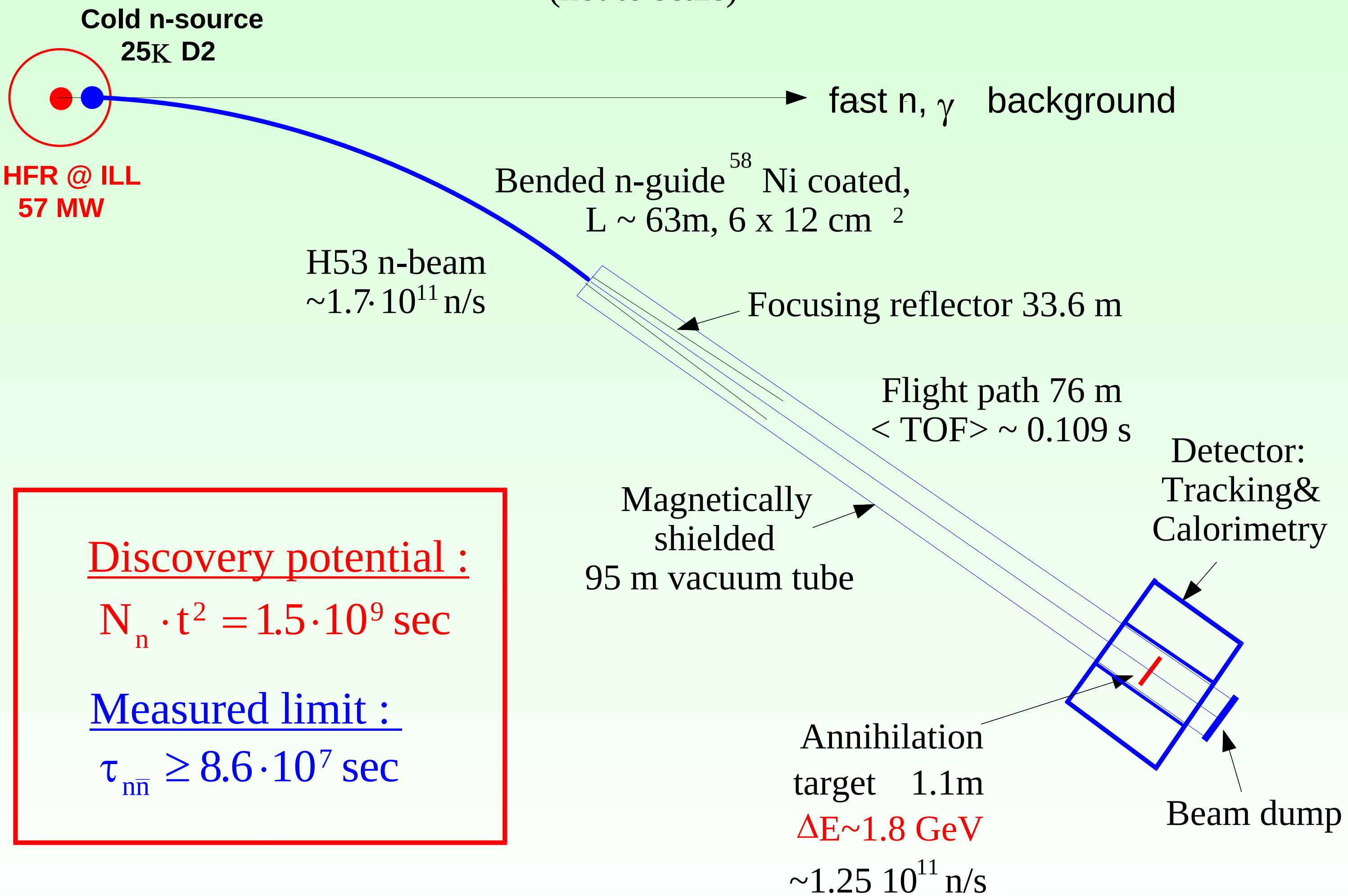
$n \to \bar{n}$ transition search experiments with free neutrons

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

UCN neutrons have not been tried so far !

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 :

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

Detector of Heidelberg -ILL-Padova-Pavia Experiment @ILL 1991

(size typical for HEP experiment)

No background;
no candidates observed
for a year of running →
measured limit:

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

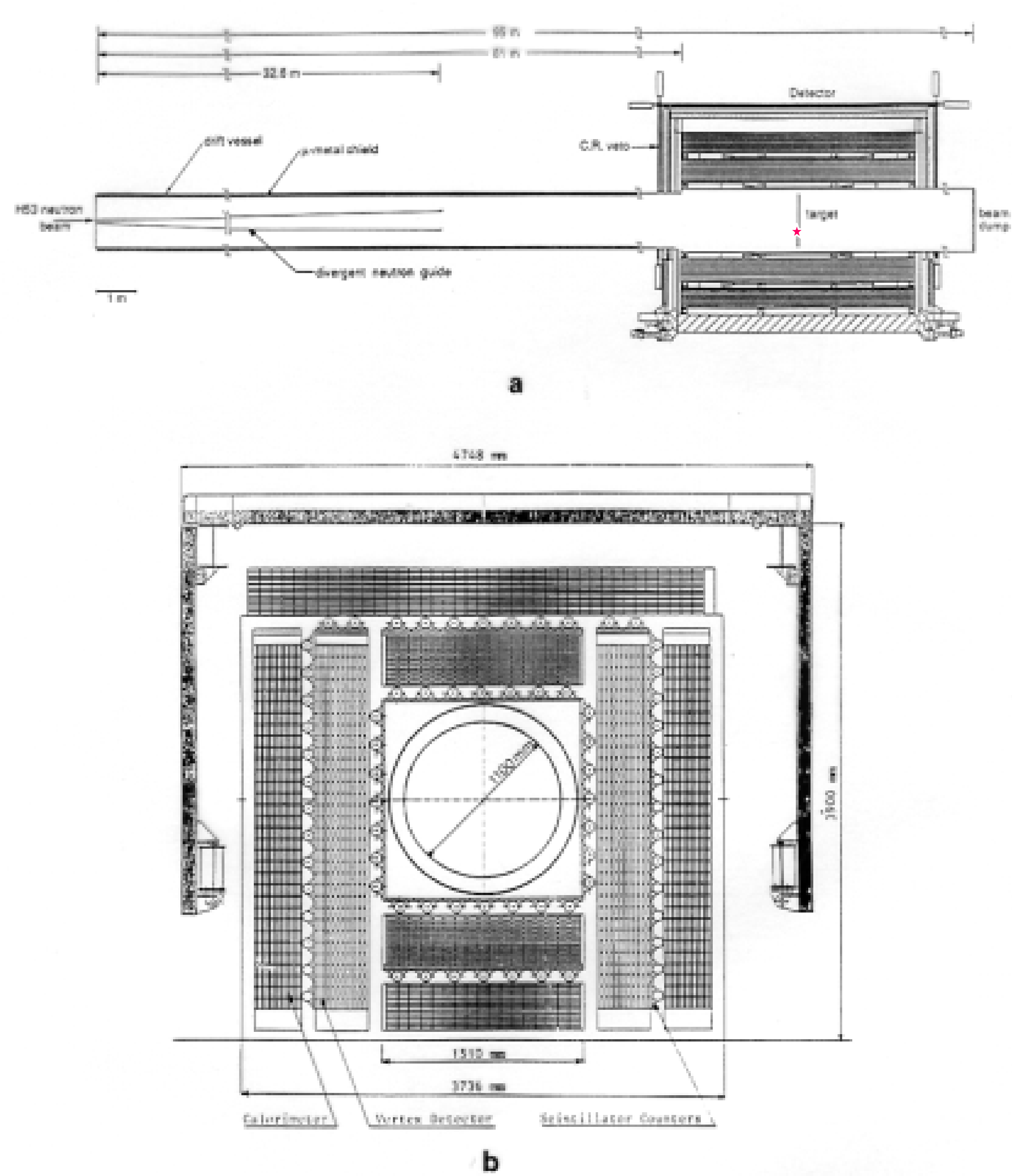


Fig. 1. (a) Experimental apparatus showing the "quasi free" neutron propagation length with the divergent guide, the target and the detection system. (b) Cross sectional view of the detector.

ILL: Institute Max Von Laue-Paul Langevin in Grenoble

Suppression of $\mathbf{n} \rightarrow \bar{\mathbf{n}}$ in intranuclear transitions

(simple picture by V. Kuzmin)

due to nuclear potential different for neutron and anti-neutron:

$$\hat{H} = \begin{pmatrix} m+V & \alpha \\ \alpha & m-V \end{pmatrix} \qquad P_{n\rightarrow\bar{n}}(t) = \frac{1}{2} \cdot \frac{\alpha^2}{\alpha^2 + V^2} \cdot (1 - \cos\omega t)$$

Neutrons inside nuclei are "free" for the time: $\Delta t \sim \frac{1}{E_{binding}} \sim \frac{1}{10MeV} \sim 10^{-22} s$

and "experience" this condition N times per second: $\rightarrow$ $N \sim \frac{1}{\Delta t}$

Transition probability per second: $P_A = \frac{1}{\tau_A} = \left(\frac{\Delta t}{\tau_{n\bar{n}}}\right)^2 \cdot \left(\frac{1}{\Delta t}\right)$ and

$$\boxed{\tau_A = \frac{\tau_{n\bar{n}}^2}{\Delta t} = R \cdot \tau_{n\bar{n}}^2} \qquad R \sim \frac{1}{\Delta t} \sim 10^{22} s^{-1}$$ “nuclear suppression factor”

Intranuclear neutron → antineutron transitions:

Soudan II'2002	$\tau_A \geq 7.2 \cdot 10^{31}$ years (Fe) (New!)
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)

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" ~ 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

N→Nbar search limit of large detectors

(Reviewed at Indiana University Workshop on n-nbar search with UCN, September 13-14, 2002)

- New Soudan II 2002 limit for n→nbar search *(T. Mann)*

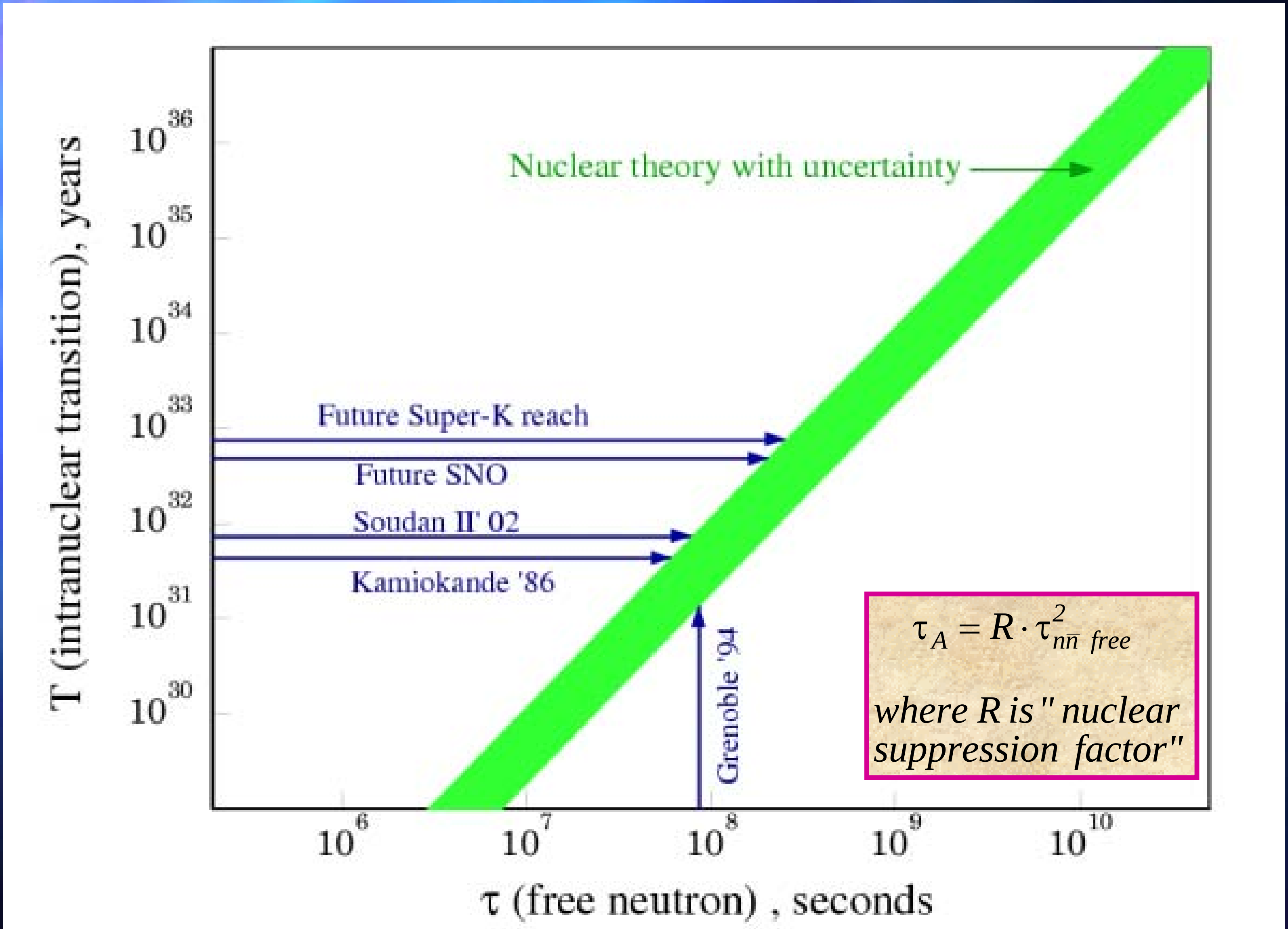
$$\text{Soudan II limit} \qquad \tau_{Fe} > 7.2 \times 10^{31} \text{ years}$$

- Future limits expected from SNO *(J. Formaggio)* and Super-K *(Ken Ganezer)*
(guesstimate of T. Mann)

$$\text{Future reach of SNO} \quad \tau_{O} \sim 4.8 \times 10^{32} \text{ years}$$
$$\text{Future reach of S-K} \quad \tau_{O} \sim 7.5 \times 10^{32} \text{ years}$$

- Since sensitivity of SNO, Super-K, and future large underground detectors will be limited by atmospheric neutrino background (as demonstrated by Soudan II experiment, it will be possible to set a new limit, but difficult to make a discovery.

Present search limits of N→Nbar transition



$$\tau_A = R \cdot \tau^2_{n\bar{n}\ free}$$

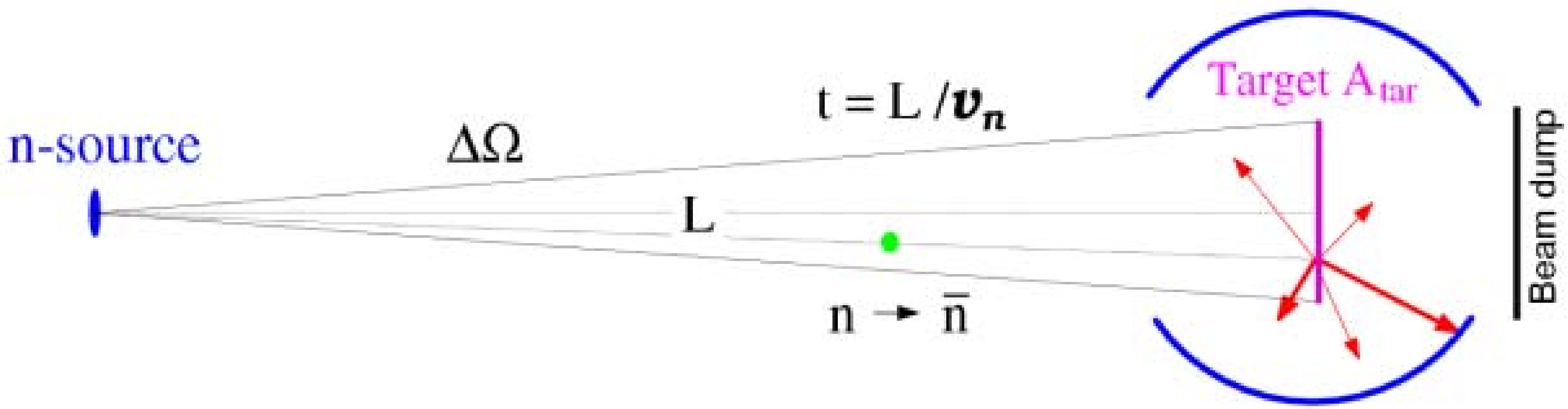
where R is "nuclear suppression factor"

$$\tau_{bound} = R \cdot \tau^2_{free}$$

Free neutrons are more advantageous for N→Nbar search

How to improve sensitivity of experiments with free neutron?

Naive scheme of $n\bar{n}$ experiment



Without neutron focusing:

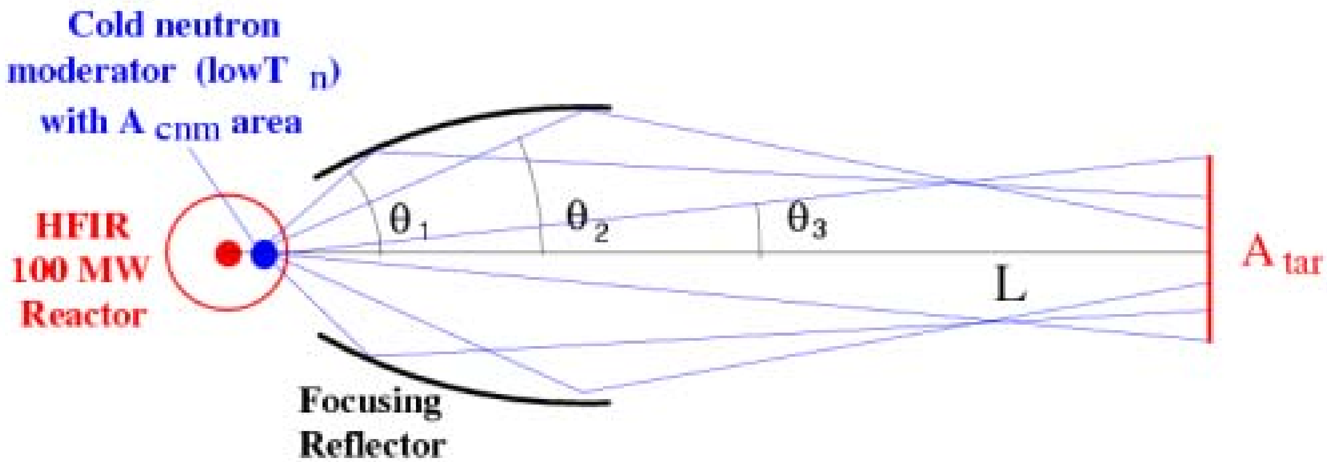
$$\Delta\Omega = \frac{A_{tar}}{L^2}; \quad D.P. = N_n \cdot \Delta\Omega \cdot (t)^2 = N_n \cdot \frac{A_{tar}}{L^2} \cdot \frac{L^2}{v_n^2}$$

Discovery potential doesn't depend on L !

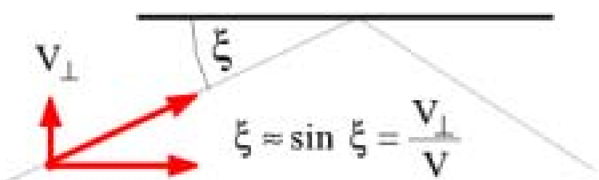
Detector:
$\Delta E \cong 1.8$ GeV
+ vertex
Typically 5 pions
per $\bar{n}$ annihilation

Schematic layout of a new experiment with focusing reflector

(not to scale)



Reflection :



$$\xi \approx \sin\,\xi = \frac{v_\perp}{v}$$

$$\Delta\Omega \sim \xi^2 \sim \frac{1}{v^2} \sim \frac{1}{T^oK}$$

$$\theta_1 < \theta < \theta_2 \rightarrow \Delta\Omega; \;\; \Delta\Omega \sim \left(\frac{1}{T_n}\right)$$

$$\text{D.P.} \sim N_{\bar{n}} \sim \Phi_n \cdot A_{cnm} \cdot \frac{\Delta\Omega}{4\pi} \cdot \left(\frac{L}{V_n}\right)^2; \;\; \Phi_n \sim V_n$$

$$\text{D.P.} \sim N_{\bar{n}} \sim \frac{L^2}{T_n^{3/2}}$$ (if no gravity)

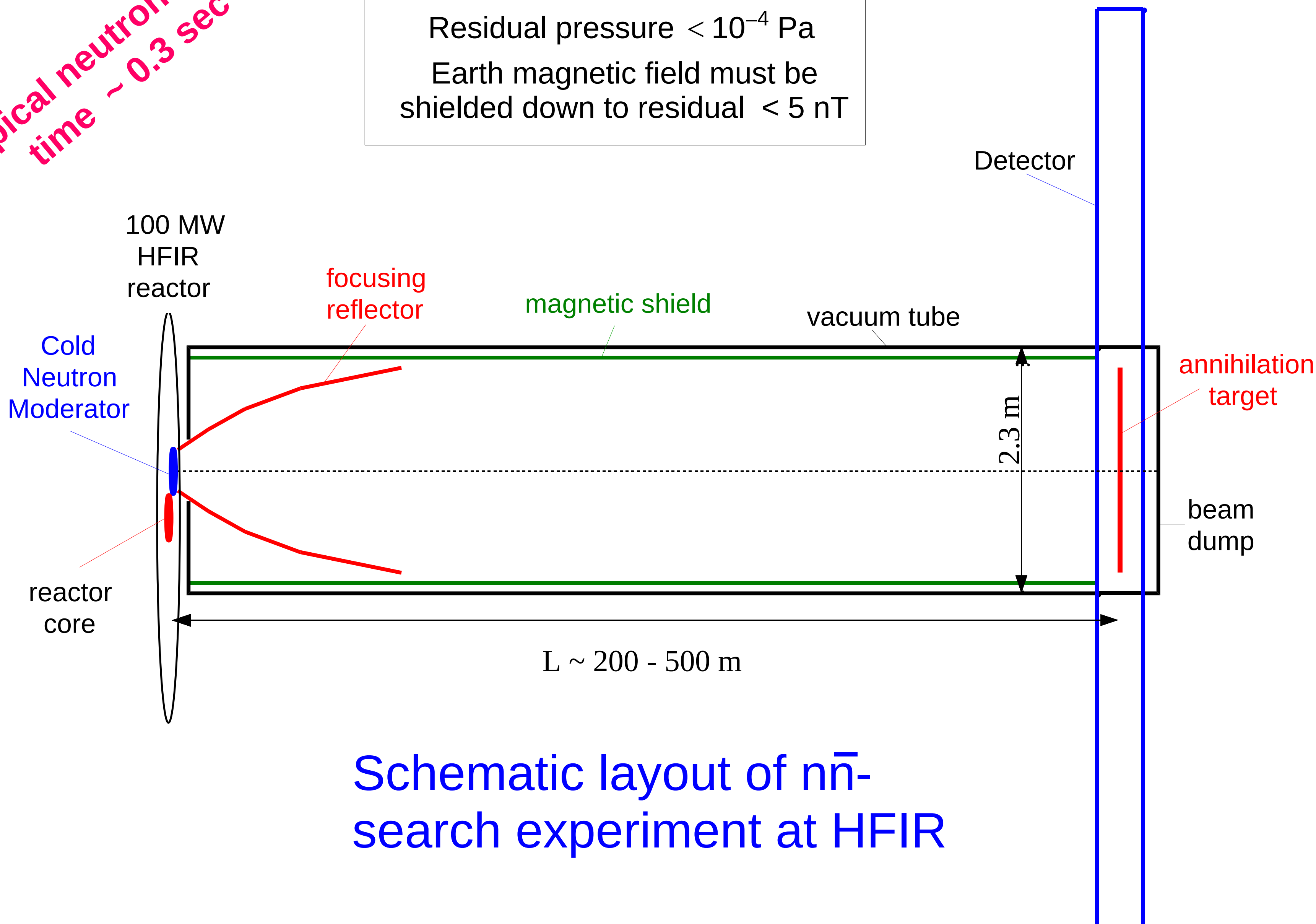
When focusing reflector is used, the large distance L and low neutron temperature T_n are most essential for discovery potential improvement

Typical neutron flight time ~ 0.3 sec

Technical issues

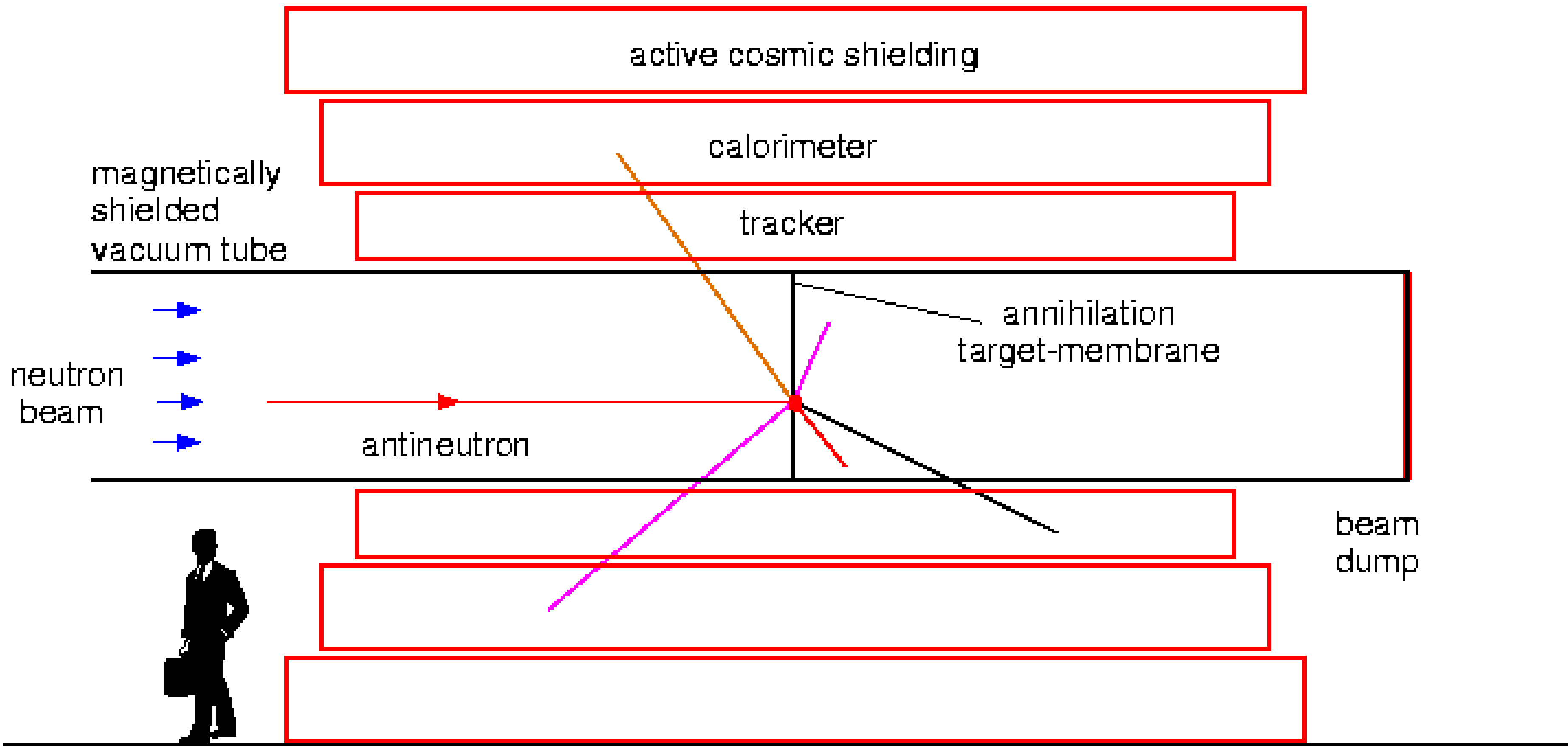
Residual pressure $< 10^{-4}$ Pa

Earth magnetic field must be shielded down to residual < 5 nT

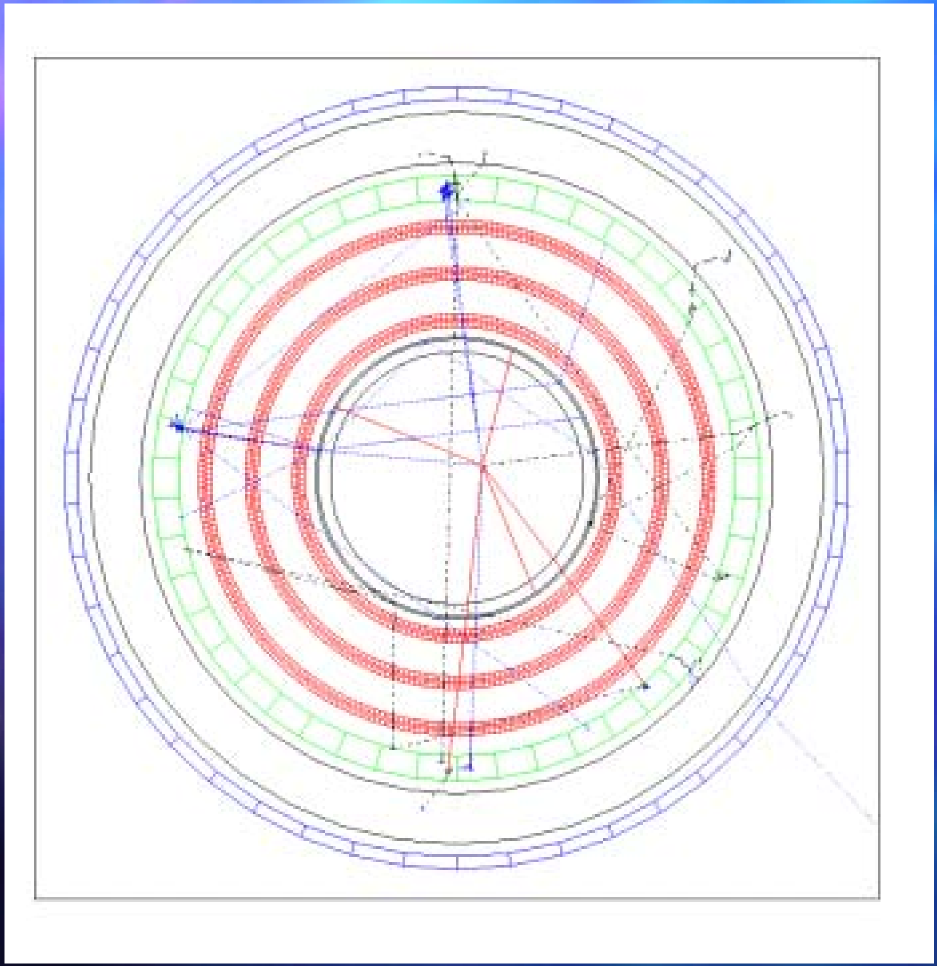


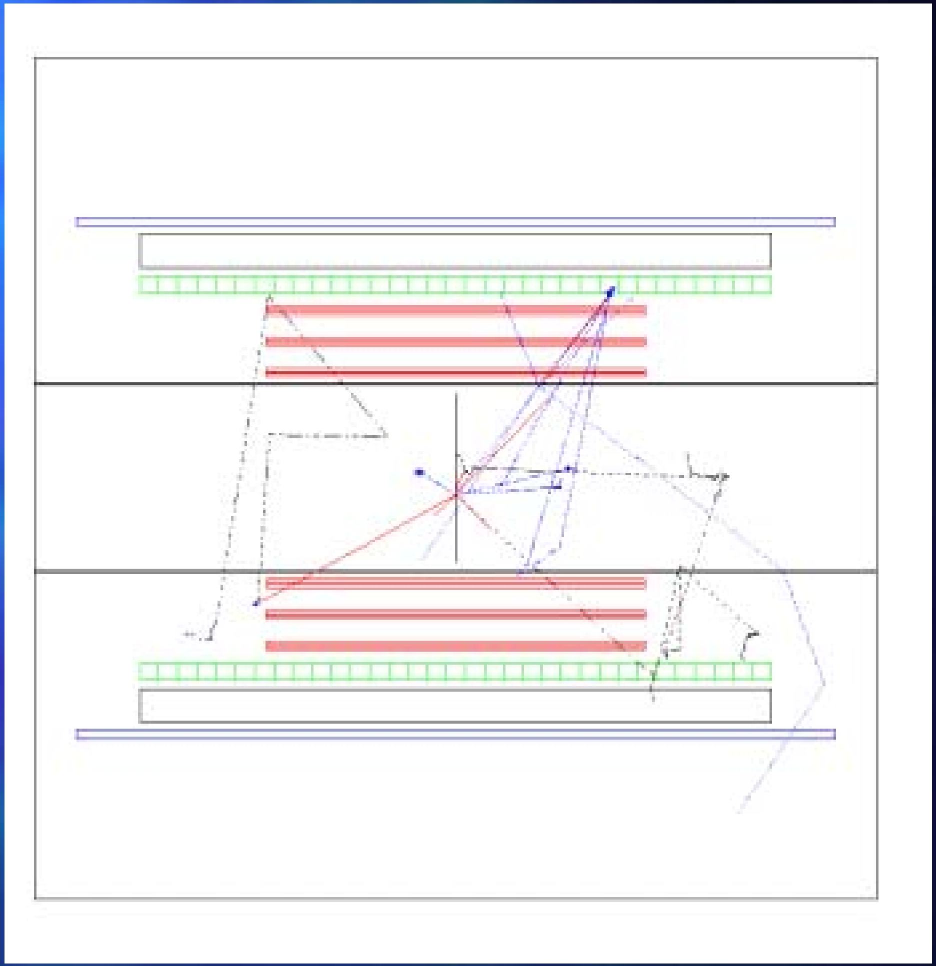
Schematic layout of $n\bar{n}$-search experiment at HFIR

The conceptual scheme of antineutron detector



Monte Carlo simulated antineutron annihilation event in N-Nbar Detector





Intranuclear anti-neutron-carbon annihilation model/generator
(1996, E. Golubeva, A. Iljinov, et al.)

Antineutron detection is well understood

(thanks to LEAR physics)

$$\bar{n} + A \rightarrow \langle 5 \rangle \ pions \quad (1.8 \text{ GeV})$$

Target: ~100μ thick Carbon film

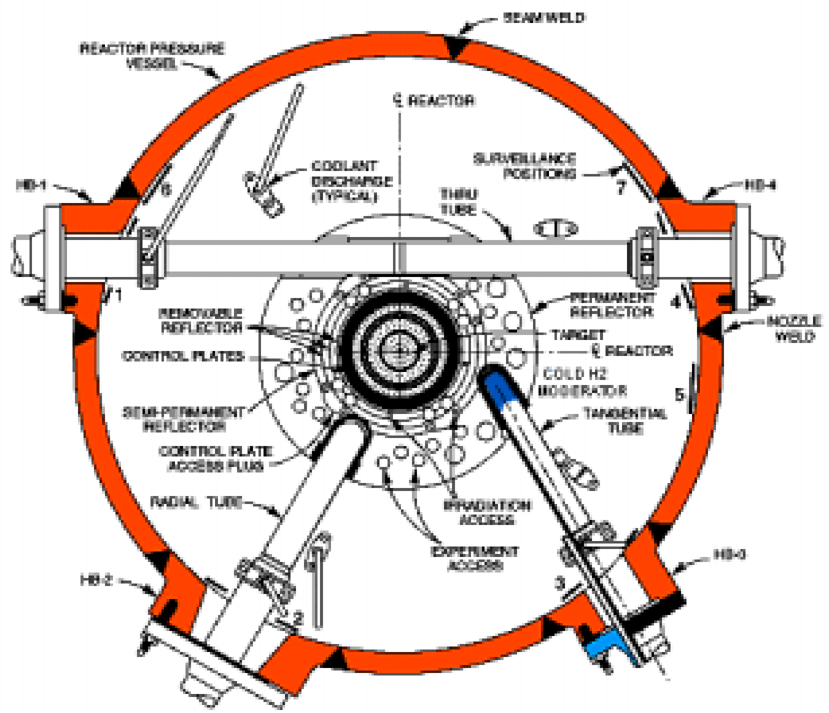
$\sigma_{annihilation} \sim 4$ Kb $\qquad \sigma_{nC\ capture} \sim 4$ mb

(Typical cold neutron: $E \approx 6$ meV; $v \approx 1000$ m/s; $\lambda \approx 4$ Å)

High-Flux Isotope Reactor
at Oak Ridge National Laboratory
where sensitivity of n-nbar search
can be increased from the present
level by factor of >1,000

$$\tau_{n\bar{n}} > 3\times10^{9}\ \text{sec}$$

With no background
one event can be a discovery!



Unfortunately, this US national facility, managed by BES/DOE, has different scientific priorities. HFIR is not available for N→Nbar search experiment.

Very strong support of HEP and NP communities in US is needed to change this attitude.

New approach: Ultra-Cold Neutrons (UCN)

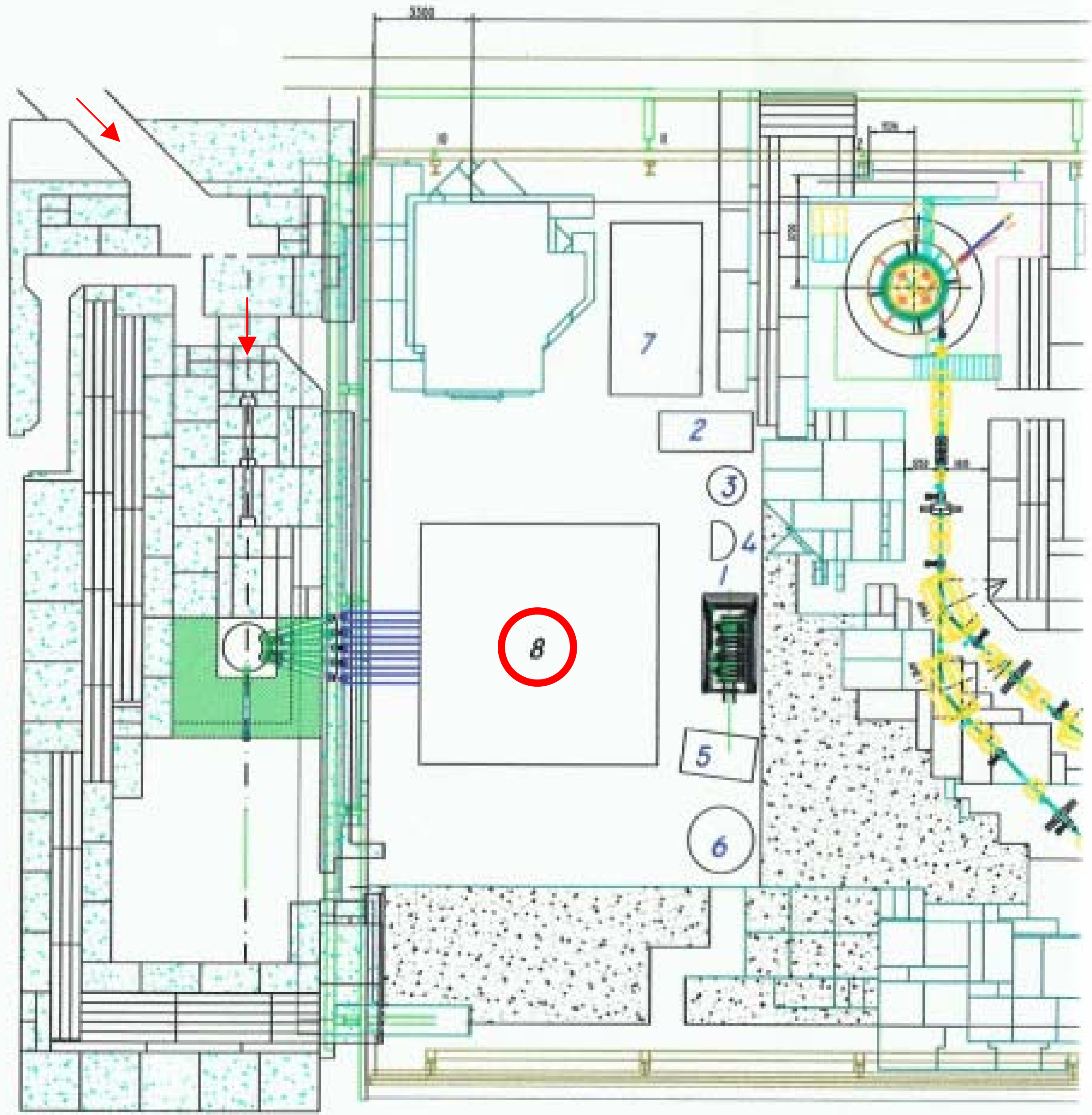
Typical UCN: E ≈ 100 neV, v ≈ 6 m/s, λ ≈ 600Å

- Recent progress in UCN production/storage: from ~ 40 ucn/cc (ILL/Grenoble) to to ~ 150 ucn/cc (Los Alamos) → 400 ucn/cc → 10^4 ucn/cc by using solid D_2 converter at 5 K.
- This technique (due to finite thermal conductivity of D_2) can provide UCN production rate up to $2 \cdot 10^7$ UCN/sec even at low-power spallation sources or reactors.
- Based on this technique several labs are building or planning UCN production facilities: PSI at Zürich, FRMII at München, North Carolina State University Reactor, Compact Neutron Source at Indiana University, StPNPI at Gatchina. Dedicated UCN target facility is proposed for 10 MW ESS.
- Plans for N-Nbar search are being discussed at some of these facilities.

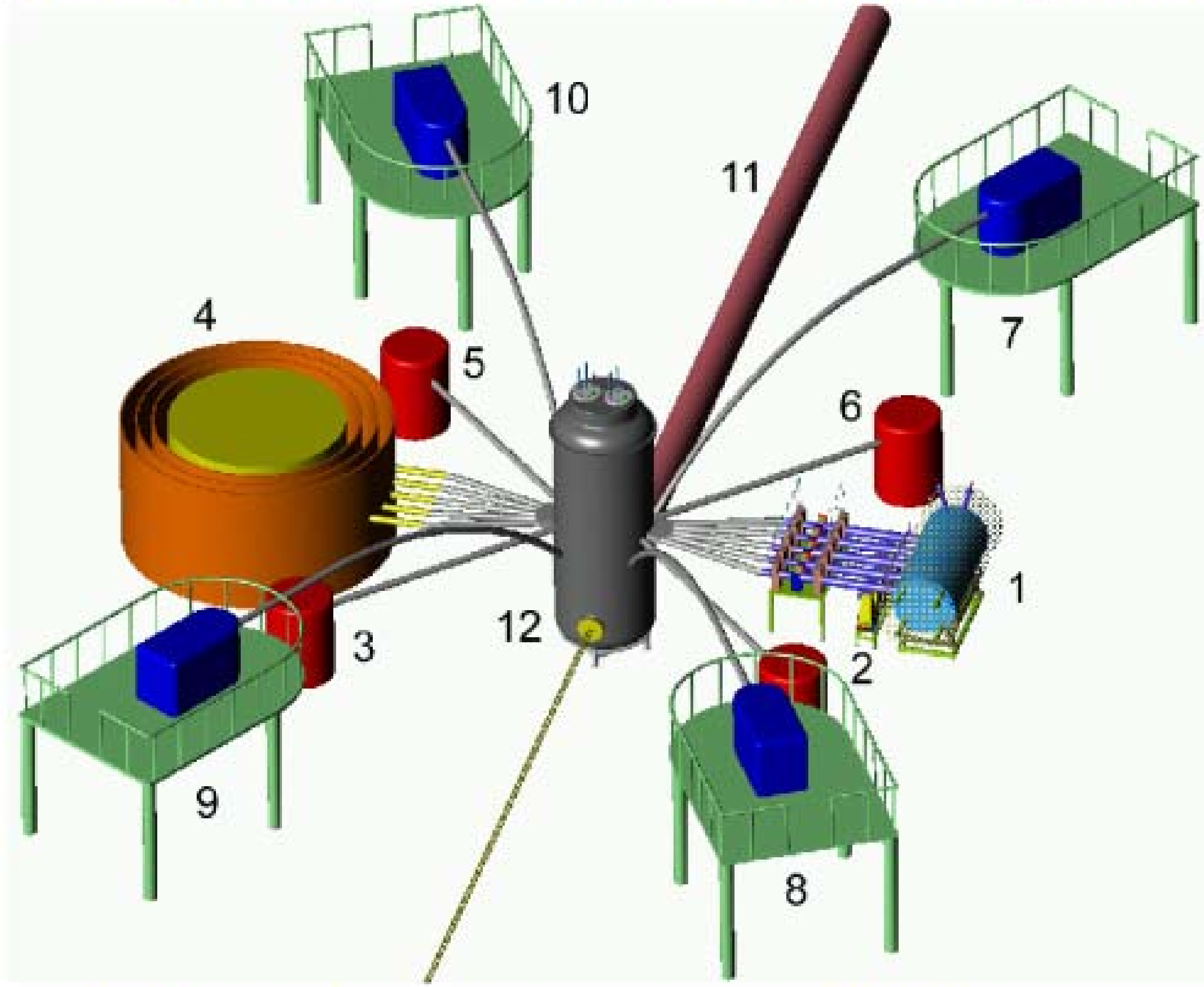
UCN factory under construction at PSI/Zürich

Dedicated proton beam
with duration 4 sec
every 400 sec

1. EDMS
2. A,B - β DECAY
3. τ_n - β DECAY
4. ANOMALOUS LOSSES
5. UCN IRRADIATION FACILITY
6. UCN MICROSCOPE
7. N-RADIOGRAPHY
8. N-Ñ BAR EXPERIMENT



Experimental Facilities of UCN Factory for ESS



1 – **neutron EDM experiment**

2, 3, 5, 6 – **UCN setup**

4 – **n-nbar experiment**

7, 8, 9, 10 – **VCN setup**

11 – **proton beam**

12 – **UCN Factory (without shielding)**

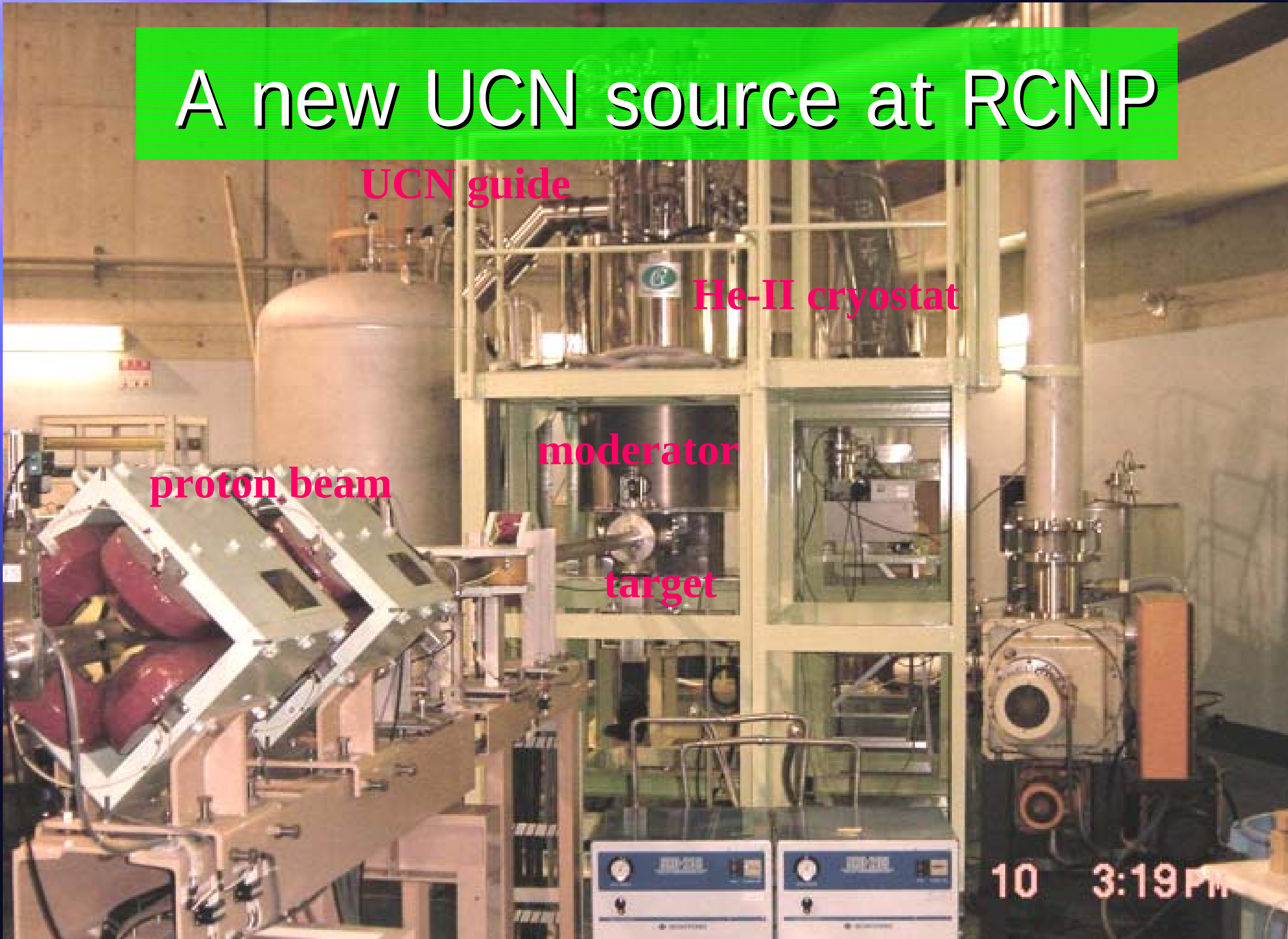
N-Nbar search with UCN

UCN lifetime in the large storage bottle can be ~ 600 s, i.e. much larger than in approach with cold neutron beam (~ 0.3 s). However, the sensitivity gain is not quadratic with time but rather linear. Since nuclear potential of the wall is different for two components of neutron-antineutron wave function, t^2-clock resets at the collision.

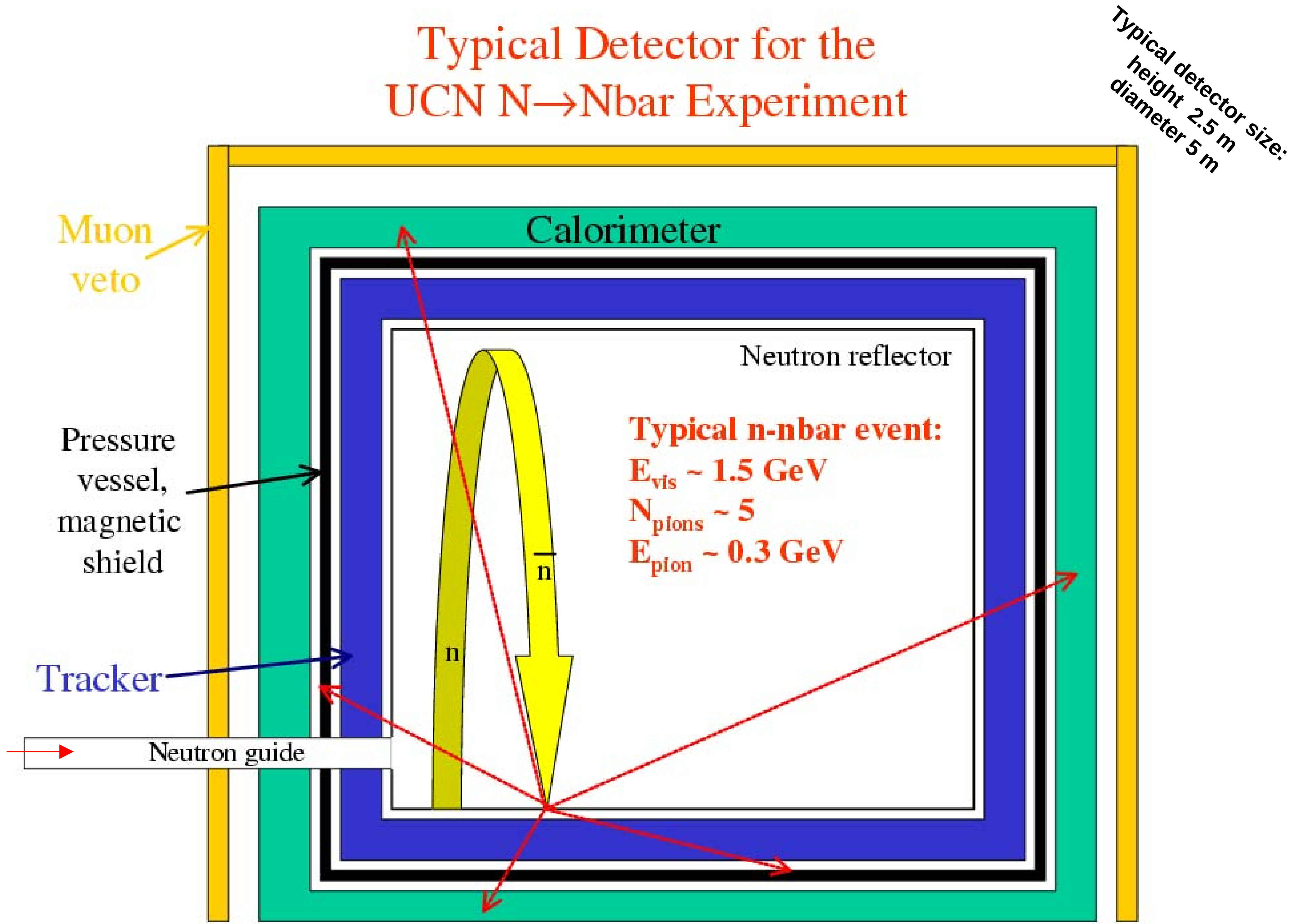
Whether the materials of the wall can be "tuned" to minimize the loss of coherence of N-Nbar wave function , is an interesting quantum mechanics problem that is not yet completely understood.

New UCN production technique being developed in Japan by Y. Masuda and his collaborators, based on super-fluid He converter, potentially offers highest UCN production rates (even with low-power neutron sources) $> 6 \cdot 10^7$ UCN/s corresponding in small volumes to UCN density ~ $2 \cdot 10^5$ ucn/cc. This production rate should allow with sufficiently large detector reach a sensitivity corresponding to N-Nbar oscillation time $> 1 \cdot 10^9$ s (assuming reset of wave function).

A new UCN source at RCNP



Typical Detector for the UCN N→Nbar Experiment



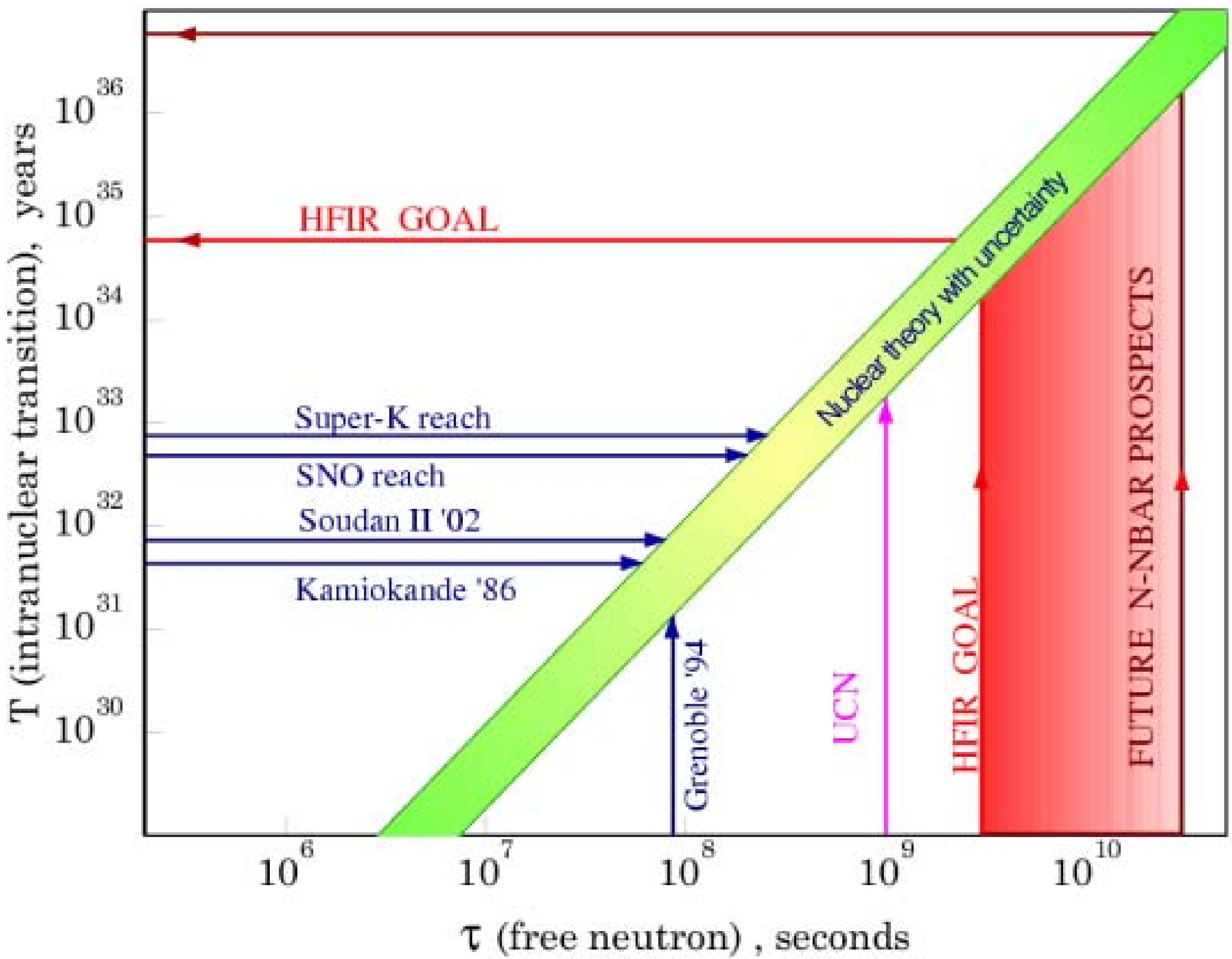
$n \rightarrow \bar{n}$ Search Sensitivity

Soudan II limit ≈ Grenoble limit = 1 unit (1 u) of sensitivity

Method	Present limit	Possible future limit	Possible sensitivity increase factor
Intranuclear (in N-decay expts)	$7.2 \cdot 10^{31}$ yr = 1u (Soudan II)	$7.5 \cdot 10^{32}$ yr (Super-K) $4.8 \cdot 10^{32}$ yr (SNO)	$\times$ 16 u (*)
UCN trap	none	$\sim 1 \cdot 10^{9}$ s	$\times$ 100 u (**)
Not direct → Geo-chemical (ORNL)	none	$4 \cdot 10^{8} \div 1 \cdot 10^{9}$ s (Tc in Sn ore)	$\times$ 20÷100 u (*)
Not available → Cold reactor beam	$8.6 \cdot 10^{7}$ s = 1u (@ILL/Grenoble)	$> 3 \cdot 10^{9}$ s (@HFIR/ORNL)	$\times$ 1,000 u (***)

Stability of matter from Neutron-Antineutron transition search

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



CPT test ($m = \overline{m}$?) in $n \to \overline{n}$ transitions

(if the latter can be observed)

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

$$i\hbar \frac{\partial \Psi}{\partial t} = \hat{H}\Psi, \quad \text{where} \quad \hat{H} = \begin{pmatrix} m_n & \alpha \\ \alpha & m_{\overline{n}} \end{pmatrix}, \quad \Delta m = m_{\overline{n}} - m_n \quad \text{(assuming no external fields)}$$

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

If $\alpha \neq 0$, then $n \to \overline{n}$ transition exists. If then Δm would be larger than $\sim 1/t_{obs}$, the $n \to \overline{n}$ transition of free neutrons in vacuum will be suppressed, but the intranuclear $n \to \overline{n}$ transitions will not be suppressed significantly more than they already 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^0s

With $n \to \overline{n}$ transitions the Δm=m can be tested

down to $\Delta m/m \sim 10^{-23}$, i.e. below the $m_n/m_{Plank} \cong 10^{-19}$

Why we need to search for n-nbar?

If discovered:

- $n \to \bar{n}$ will establish a new force of nature and a new phenomenon leading to the physics at the energy scale of $\sim 10^5$ GeV.
- Will provide an essential contribution to the understanding of BAU.
- New physics emerging from low quantum gravity scale models can be revealed.
- New symmetry principles can be experimentally established: $\Delta(B-L) \neq 0$.
- Further experiments with UCN and free reactor neutrons will allow testing with high sensitivity:

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

– gravitational equivalence of baryonic matter and antimatter *(S. Lamoreaux et al.)*

If NOT discovered:

- Within the reach of improved experimental sensitivity a new limit on the stability of matter can be established competitive with that in large nucleon decay experiments.
- 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 though to work for BAU	• Proton decay is not a prediction of baryogenesis! 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	• No Desert. 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 should look for* $n \to \bar{n}$ *and* $B-L$ *violation*

UCN production technique being developed in Japan offers the best opportunity to search for neutron-antineutron transition and hopefully to discover it …