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Neutron → Antineutron Search

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Explanation of baryon asymmetry of the universe (BAU) requires

[A. Sakharov, 1967, V. Kuzmin 1970]

(1) Baryon number violation

(2) C and CP symmetry violation

(3) Departure from thermal equilibrium

BAU does not define the particular modes of baryon number violation. These are suggested by theoretical models. One of the most popular models of 1980's the original GUT based on the SU(5) symmetry [Georgi and Glashow, 1974] and predicting proton decay into $p \to e^+ \pi^0$ with $\tau \approx 10^{31\pm1}$ years was ruled out by experiments [IMB, Fréjus, Kamiokande, Soudan-2, Super-Kamiokande]. SU(5) as well as Standard Model conserves (B–L).

(B–L) violation ?

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 created at some unification scale > 1 TeV by (B–L) conserving processes. Thus, the baryon number violation should occur together with the violation of (B–L). Baryon number violating processes where Δ(B–L)≠0 (like $n \to \nu\nu\bar{\nu}$, $p \to \nu\nu e^{+}$, $n \to \bar{n}$ *etc.*) should be preferred to the conventional nucleon decay modes (like $p \to e^{+}\pi^{0}$, $p \to \bar{\nu}K^{+}$, $p \to \mu^{+}K^{0}$, *etc.*)

If conventional proton decay modes would be discovered tomorrow by Super-K, it will not help us to understand BAU.

Due to the conservation of angular momentum, the Δ(B–L)≠0 means |Δ(B–L)|=2. Thus, the physics of (B–L) non-conservation scale should include:

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

(2) Majorana masses for the neutrinos

(3) Neutrinoless double β-decay

(4) Intranuclear 2N disappearance

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

Neutron → Antineutron Transition

- There are no laws of nature that would forbid the $n \to \bar{n}$ transitions except the conservation of "*baryon 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

In the recent models with low quantum gravity scale

$n \to \bar{n}$ 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, there are following virtual processes: brane gets curved locally and creates a bubble ("baby brane") which gets detached from the brane and goes into extra dimension where it effectively becomes a black hole, then 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 $n \to \bar{n}$ transition.

The same process cannot lead to the proton decay, since the charged particles cannot leave the brane, because the photon is localized there. The amplitude of the $n \to \bar{n}$ process depends on the parameters such as fundamental Planck mass, brane thickness etc. For reasonable values the effective operator comes out to be suppressed by the scale around 10^5 GeV or so.

[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]

$n \rightarrow \bar{n}$ transition probability in vacuum:

$$P(t) = \left(t / \tau_{n\bar{n}} \right)^2$$

i.e. proportional to the square of neutron observation time *t* ($\tau_{n\bar{n}}$ is oscillation parameter).

Sensitivity (or discovery potential) is proportional to the integral flux of neutrons *N* times the square of observation time *t*:

$$D.P. = N \cdot \langle t \rangle^2$$

Spectacular observation of $n \rightarrow \bar{n}$

would be possible with free cold neutrons
in a reactor experiment

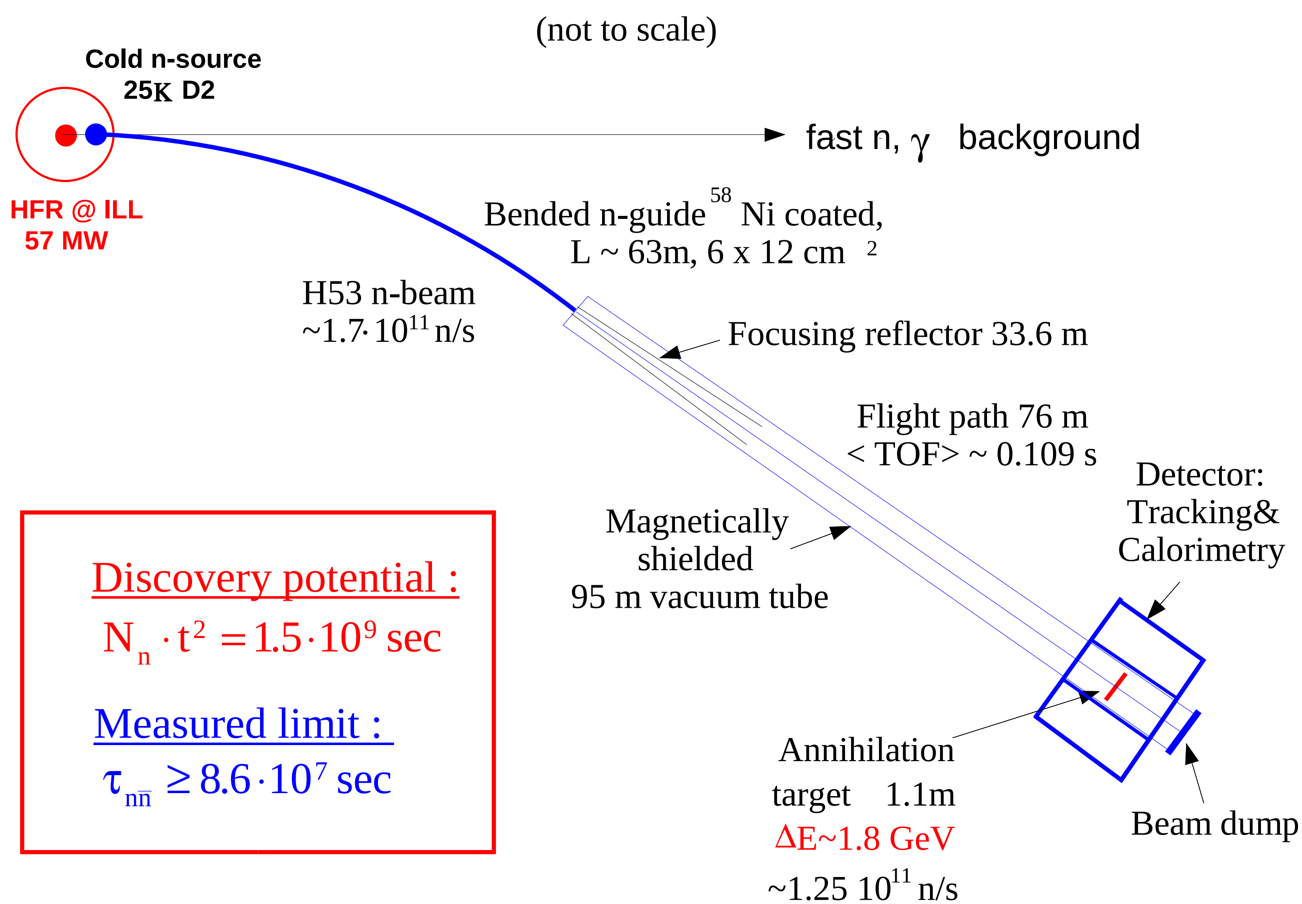
- The detection signal for cold anti-neutron interaction with nucleus is clean and unambiguous

$$\bar{n} + A \rightarrow 5\,pions\ (1.8\ GeV)$$

- Discovery potential can be increased by a large factor relative to the present experimental limit.

$$Factor\ of \sim 10^3$$

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



Discovery potential :

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

Measured limit :

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

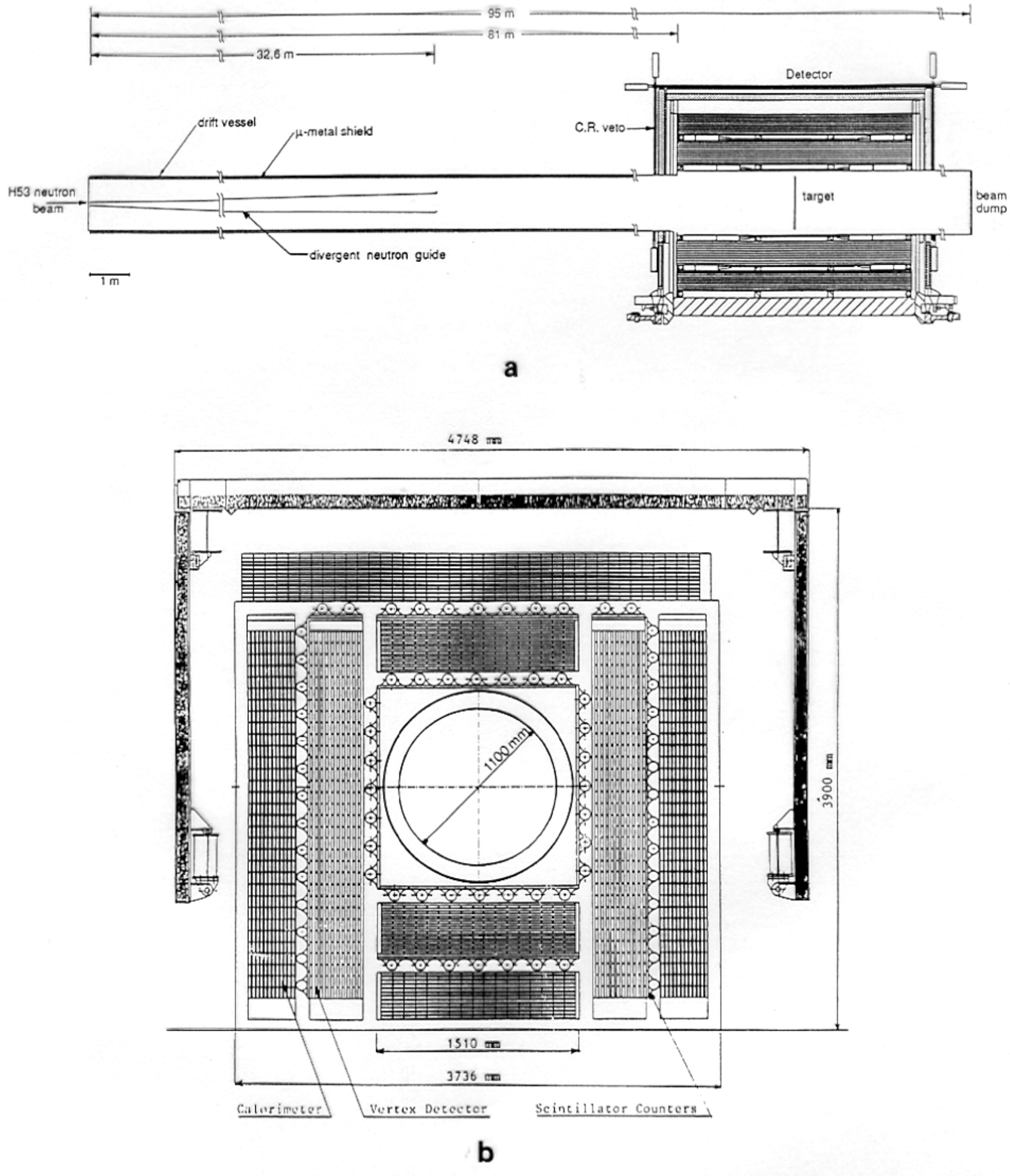
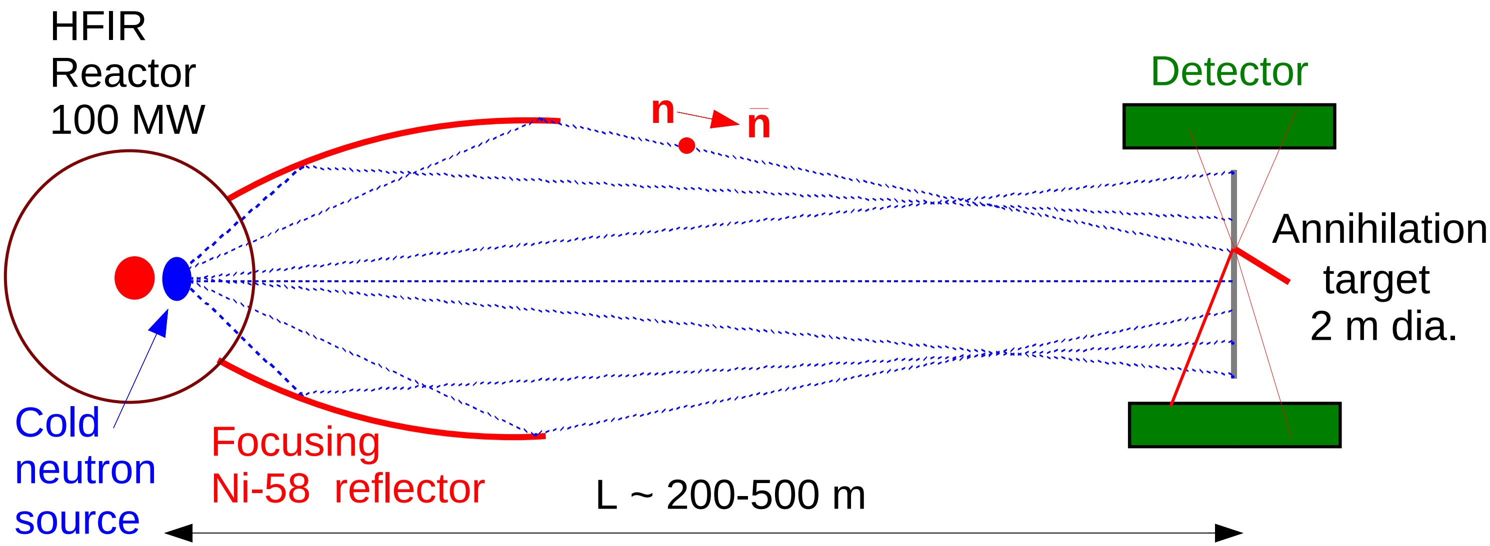


Fig. 1. (a) Experimental apparatus showing the "quasi free" neutron propagation length with the divergent guide, the target and the detection system. (b) Cross sectional view of the detector.

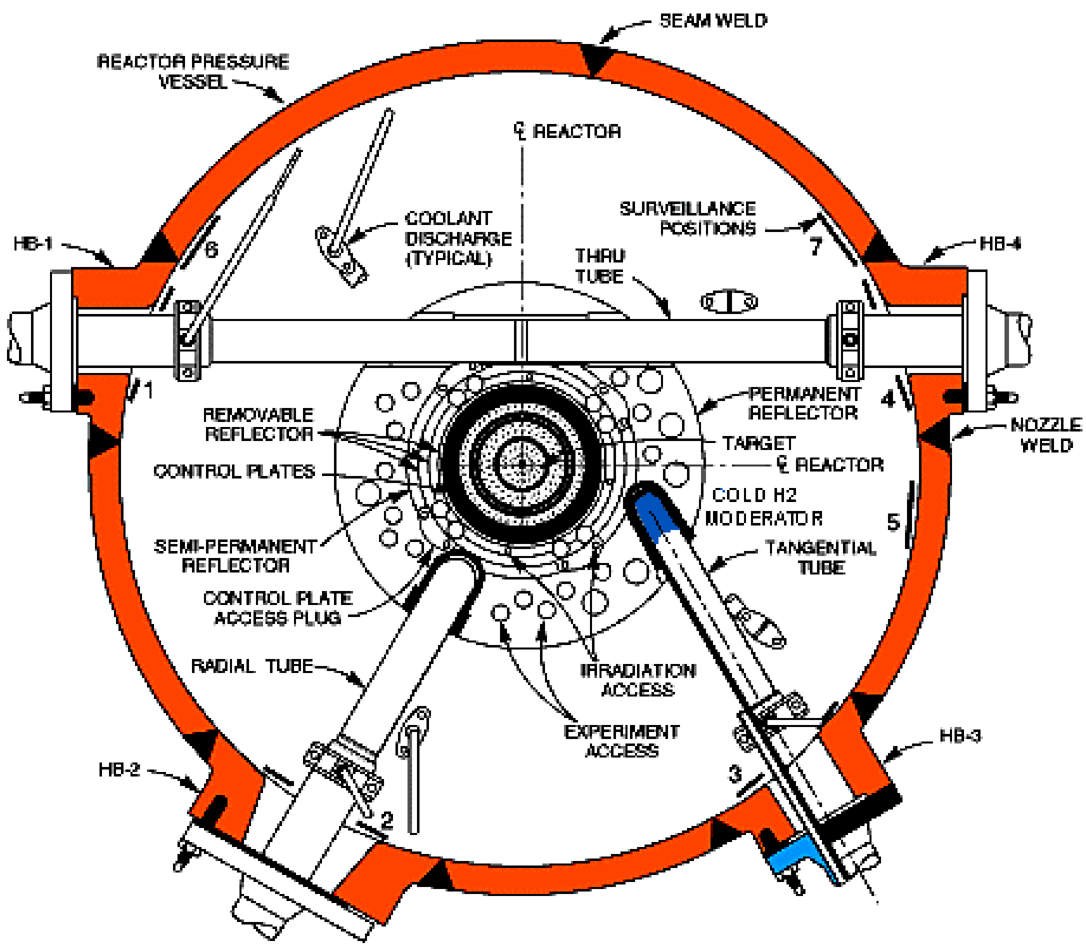
Detector of Heidelberg-ILL-Padova-Pavia Experiment

New advanced layout for HFIR/ORNL



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

High-Flux Isotope Reactor at Oak Ridge National Laboratory

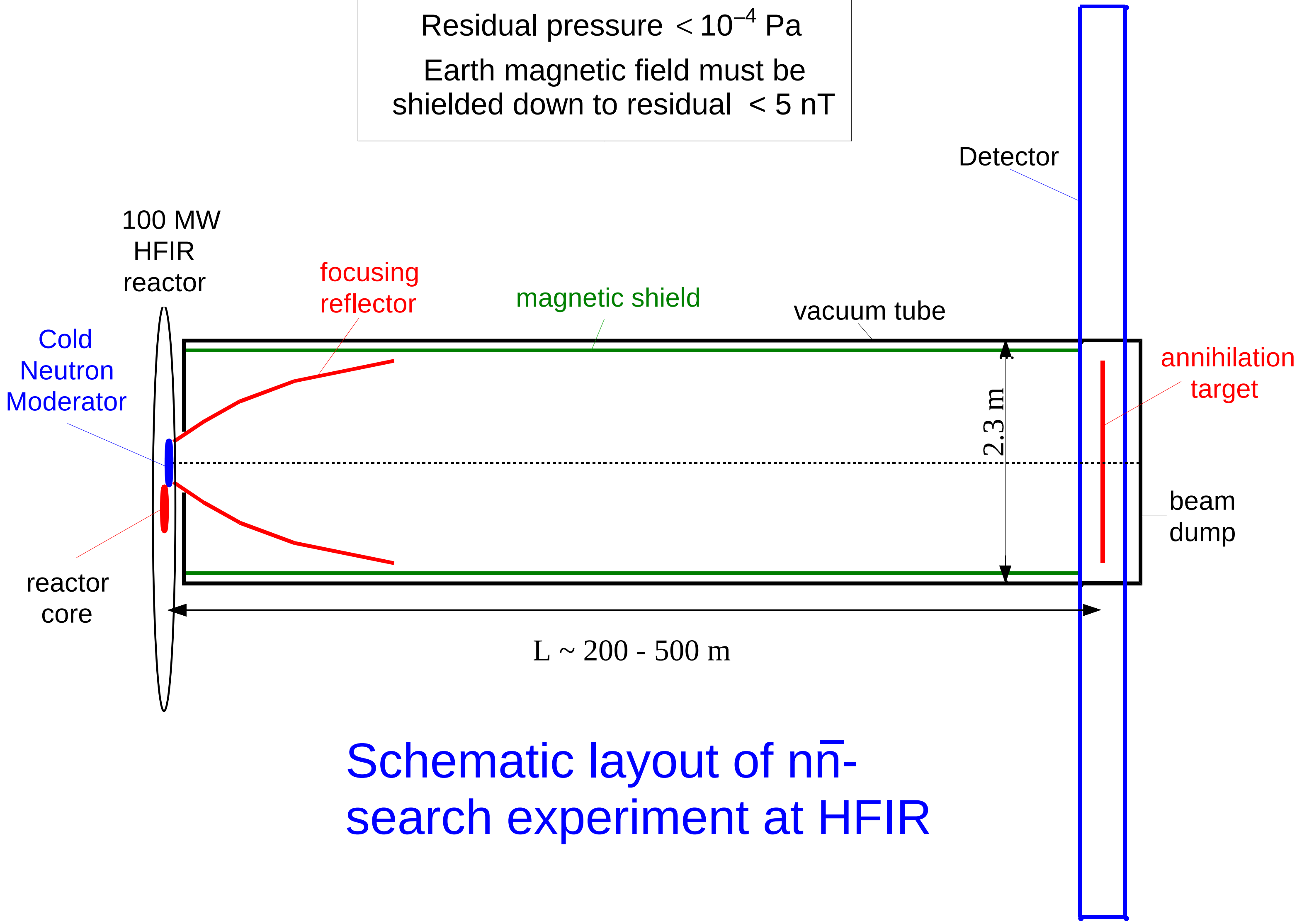


Section view of ORNL/HFIR reactor core. For the $n \rightarrow \bar{n}$ search experiment the cold supercritical hydrogen moderator should be installed in the HB–3 beam tube.

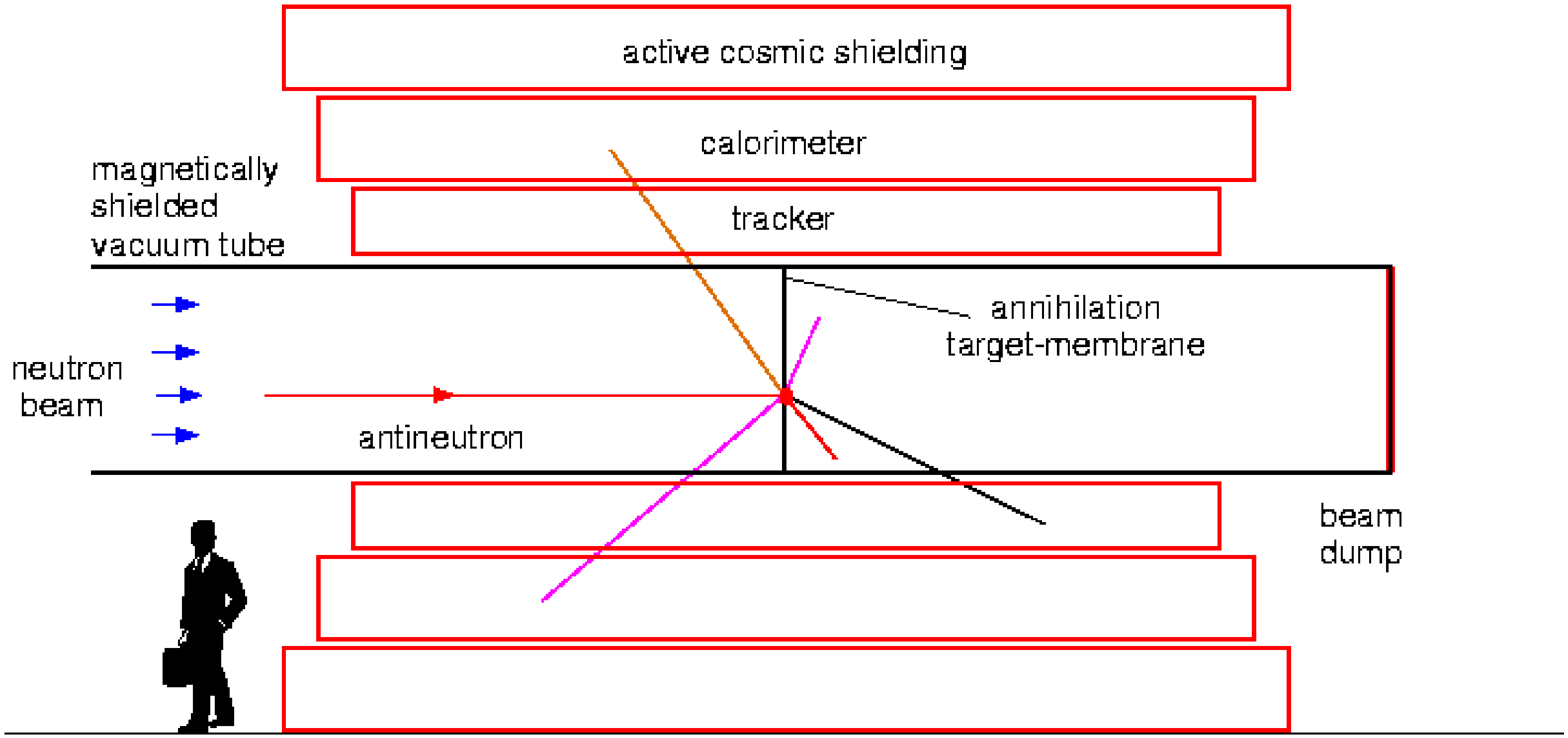
Technical issues

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

Comparison

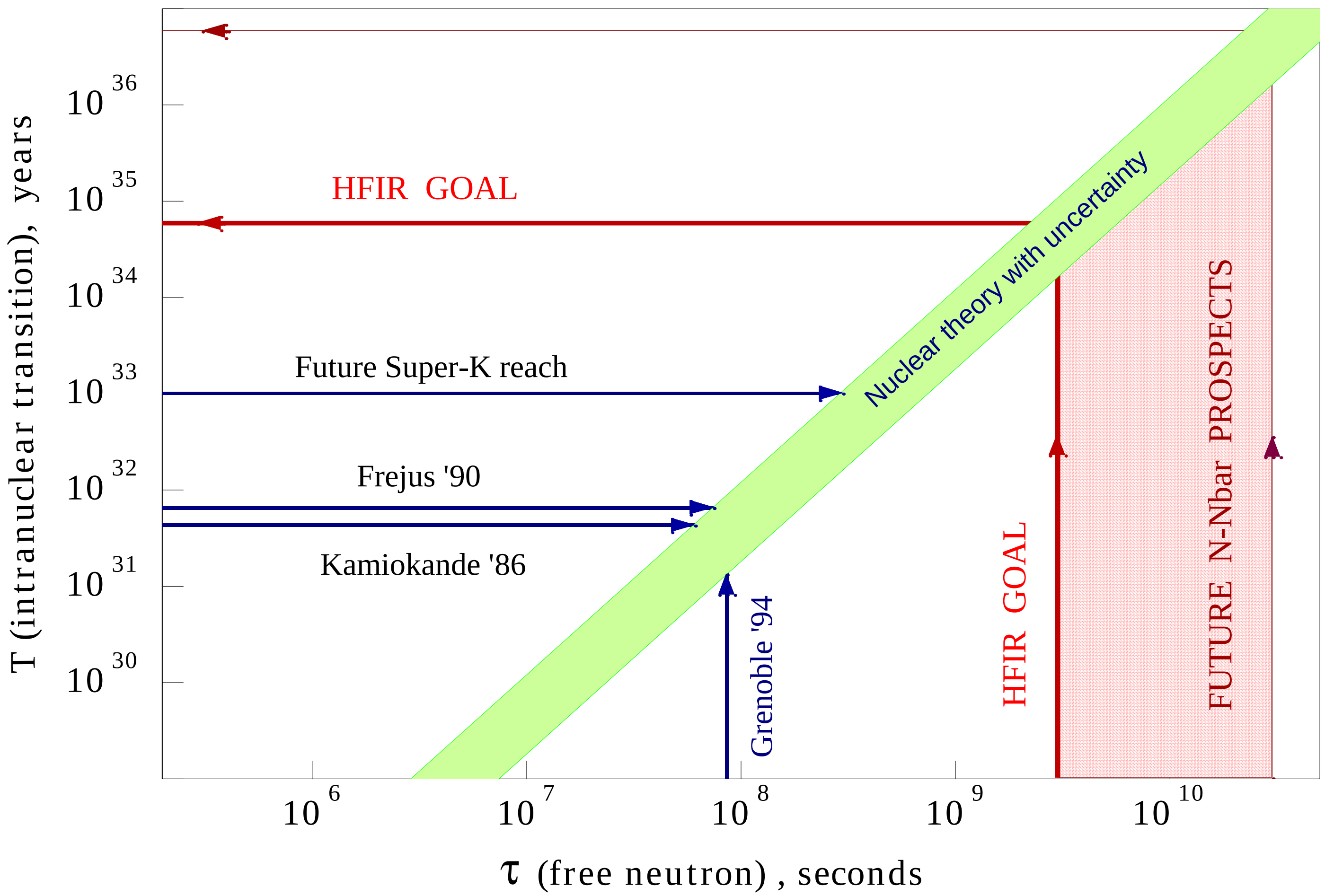
of the major parameters of the new $n \rightarrow \bar{n}$ search experiment proposed for HFIR HB–3 beam at ORNL with another recent reactor-based experiment.

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 Grenobl

Stability of matter from Neutron-Antineutron transition search

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



Scientific reach of $n \to \bar{n}$ experiment

Search for $n \to \bar{n}$ transitions
would address following fundamental questions:

– *are nucleons stable?*
– *how did the universe begin?*
– *is a new theory of matter needed at high energy?*
– *are there additional space-time dimensions?*

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.

New physics emerging from the models with low quantum gravity scale can be revealed.

Will provide an essential contribution to the understanding of baryon asymmetry of the universe.

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 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 $\sim 10^{35}$ years will be established[†].

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† through theoretically well understood connection to the intranuclear $n \to \bar{n}$ transitions.

Who might be involved in $n \rightarrow \bar{n}$ search project?

ORNL that operates HFIR facility;

HEP, NP, and AP groups with the experience of operation of moderately large detectors;

Groups or individuals with the experience in fundamental neutron physics experiments;

Other National Laboratories; International groups

So far interest was expressed by physicists from:

University of Alabama	University of Tennessee
Indiana University	Triangle Universities Nuclear Laboratory
Los Alamos National Laboratory	Virginia Tech
North Carolina State University	INR, Troitsk, Russia
Oak Ridge National Laboratory	ITEP, Moscow, Russia

Cost and Schedule

- No serious cost-estimate study has been made. Major uncertainties are due to the reactor operation, certification, shielding, safety, services, cold source construction, etc.

- Based on the cost of the cold neutron source for HB-4 beam at HFIR (~$15 M) and on the cost of the previous $n \to \bar{n}$ search experiment at ILL/Grenoble (~SFr 20 M), we guesstimated the cost of the new HFIR-based experiment to be below $50 M.

- After the completion of the proposed $n \to \bar{n}$ search experiment cold neutron source at HFIR HB-3 beam can be a significant asset for the material science research at ORNL (funded by DOE/BES).

- Anticipated schedule: 2 years of Technical Design preparation; 2 years of construction; and 3 years of running.

Potential/need for multi-agency involvement

- Although physics addresses by $n \rightarrow \bar{n}$ search belongs to the fundamental high-energy physics and cosmology, it does not fall automatically into the scope of HEPAP that is concerned primarily with the future of accelerator-based physics.

- No established "tradition" of previous $n \rightarrow \bar{n}$ reactor experiments in US.

- HFIR facility is operated/programmed/funded by DOE/BES that has a different scientific and operational mission and little expertise in the physics fields related to the proposed $n \rightarrow \bar{n}$ experiment.

- Management of ORNL/HFIR has no good mechanism to support study and development of $n \rightarrow \bar{n}$ experiment.

- 9/2000: Letter to HEPAP in support of $n \rightarrow \bar{n}$ experiment (in hand-outs);
  11/2000: $n \rightarrow \bar{n}$ physics mentioned in the white paper of NSAC's Astrophysics, Neutrinos, and Symmetries Town Meeting;
  5/2001: Presentation to HEPAP town meeting at SLAC;
  7/2001: Discussion in P3 group at Snowmass

- Need for multi-agency support: primarily HEP+BES+NP in DOE and/or NSF. Due to $n \rightarrow \bar{n}$ relation to the fundamental cosmological issues, it might be probably also of interest to NASA.

Conclusions

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

1980's	2000's
• GUT models conserving (B–L) were popular for BAU	• No need for GUT; Δ(B–L)$\neq$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.*

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