ESS Science Symposium on Neutron Particle Physics at Long Pulse Spallation Sources

March 25, 2013 at the LPSC, Grenoble, France

Search for Neutron-Antineutron Transformation at Fermilab Project X

US developments towards $n \rightarrow \overline{n}$ experiment

On behalf of NNbarX Collaboration
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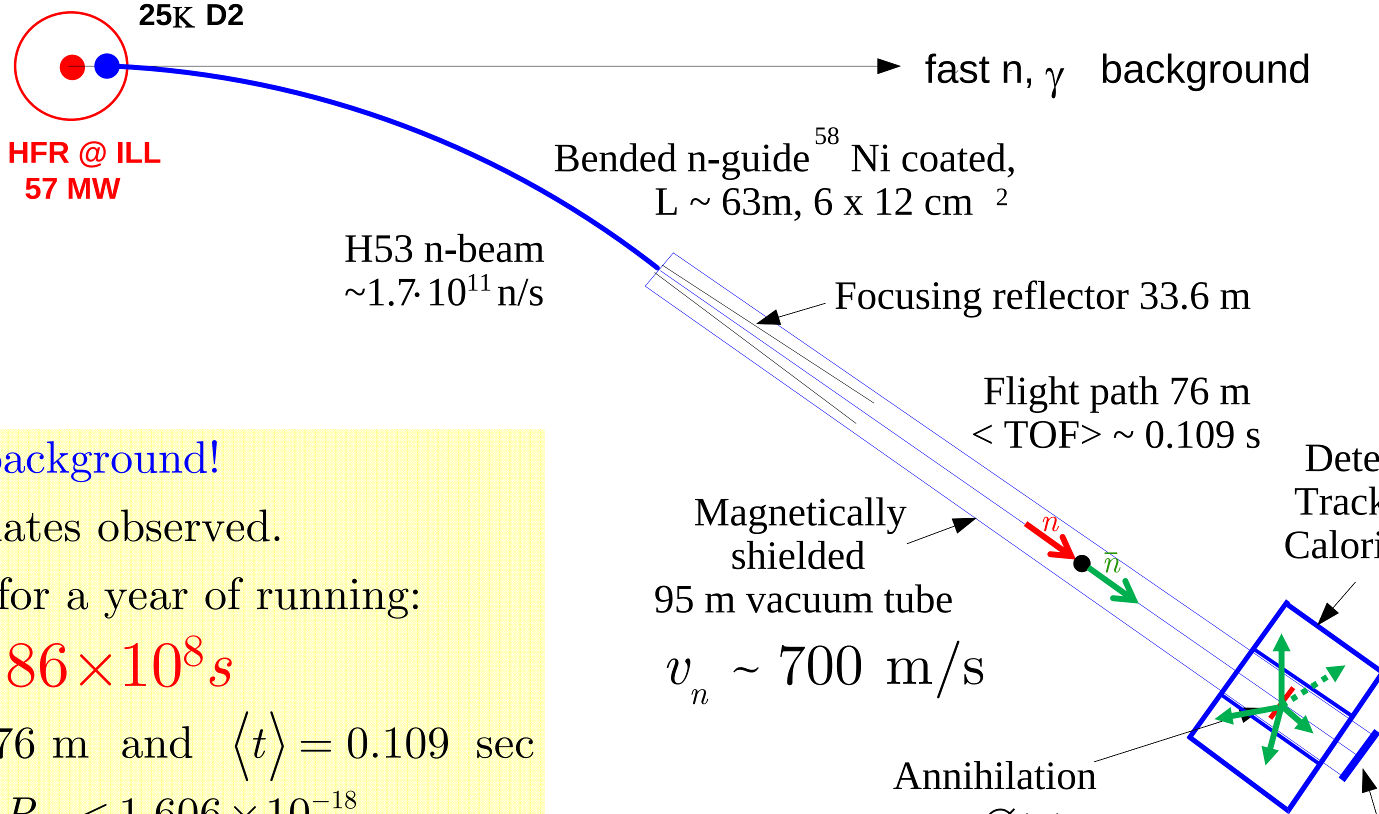
Previous state-of-the-art n-nbar search experiment with free neutrons

At ILL/Grenoble reactor in 89-91 by Heidelberg-ILL-Padova-Pavia Collaboration

M. Baldo-Ceolin et al., Z. Phys., C63 (1994) 409

(not to scale) Top view of horizontal experiment



No GeV background!

No candidates observed.

Limit set for a year of running:

$$\tau_{n\bar{n}} > 0.86 \times 10^8 s$$

with L ~ 76 m and $\langle t \rangle = 0.109$ sec

measured $P_{n\bar{n}} < 1.606 \times 10^{-18}$

sensitivity: $N \cdot t^2 = 1.5 \times 10^9 \ \ s^2/s$

$\doteq$ "ILL sensitivity unit"

Is Neutron a Majorana Particle?

In the famous E. Majorana 1937 paper
“Teoria simmetrica dell’elettrone e del positrone”,
Il Nuovo Cimento, v.14, 1937, pp. 171-184:

“ ... this method ... allows not only to cast the electron-positron theory into a symmetric form, but also to construct an essentially new theory for particles not endowed with an electric charge (neutrons and the hypothetical neutrinos).”

(translated by L. Maiani)

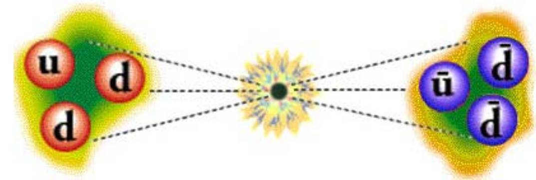
But antineutron discovered in 1956 by B. Cork et al. @ LBL was turned out to be a particle different from neutron (e.g. with different cross sections)

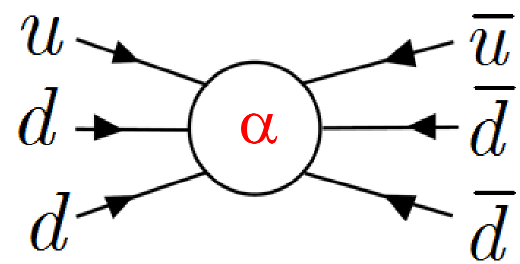
However, the presence of some small antineutron component in the neutron wave function can not be excluded, and thus the question whether neutron is Majorana particle should remain.

$$"n" = \begin{pmatrix} n \\ \overline{n} \end{pmatrix}$$

n→nbar transition probability

$$\Psi = \begin{pmatrix} n \\ \overline{n} \end{pmatrix} \quad \text{mixed n-nbar QM state}$$





α-mixing amplitude

All beyond SM physics is here

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

$$E_n = m_n + U_n \quad ; \quad E_{\overline{n}} = m_{\overline{n}} + U_{\overline{n}}$$

$$U_{n,\overline{n}} = U_0 \pm V \quad \leftarrow \quad V = \text{part different for } n \text{ and } \overline{n}$$

$$P_{n\to\bar{n}}(t) = \frac{\alpha^2}{\alpha^2+V^2}\cdot\sin^2\left(\frac{\sqrt{\alpha^2+V^2}}{\hbar}\cdot t\right)$$

where V is a potential symmetrically different for n and $\bar{n}$
(e.g. due to non-compensated Earth mag. field, or nuclear potential);
t is observation time in an experiment.

In ideal situation of no suppression
i.e. "vacuum oscillations" : $V = 0$
and experimentally t ~ 0.1 s to 10 s

$$P_{n\to\bar{n}} = \left(\frac{\alpha}{\hbar}\times t\right)^2 = \left(\frac{t}{\tau_{n\bar{n}}}\right)^2$$

$\tau_{n\bar{n}} = \frac{\hbar}{\alpha}$ is characteristic "oscillation" time [$\alpha < 2\cdot 10^{-24} eV$, as presently known]

Existing exp. limits are set by at ILL (free n) and by Super-K (bound n)

Predictions of theoretical models: observable effect around $\alpha \sim 10^{-25} - 10^{-26} eV$

Sensitivity (or figure of merit) is $\rightarrow$ $N_n \times \overline{t}^2$

n→nbar Physics Case

- Observation of violation of Baryon number is one of the pillars of the modern Cosmology and Particle Physics
  - it is required for explanation of Matter-Antimatter asymmetry or BAU (Sakharov, Kuzmin)
  - it follows from the inflation (Dolgov, Zeldovich)
  - it is motivated by GUT models (Georgi, Glashow, Pati, Salam, ...)

  Proton decay ΔB = 1 (underground) and $n \longrightarrow \overline{n}$ ΔB = 2 (n-sources) are complementary.

- (B – L) symmetry of Standard Model must be violated (Kuzmin, Rubakov, Shaposhnikov)

  → idea of Leptogenesis with ΔL = 2 with heavy Majorana fermions (Fukugita, Yanagida …)

  Majorana nature of the ν's can experimentally demonstrate ΔL = 2 and thus (B – L)V, however, experimental prove of Leptogenesis mechanism will not be likely possible.

- Most of the Proton decay searches with ΔB = 1 motivated by GUT or SUSY-GUT models are conserving (B – L) and so far failed to observe Proton decay.

  → "Proton decay with Δ(B–L)=0 is not a prediction of baryogenesis" (Yanagida).

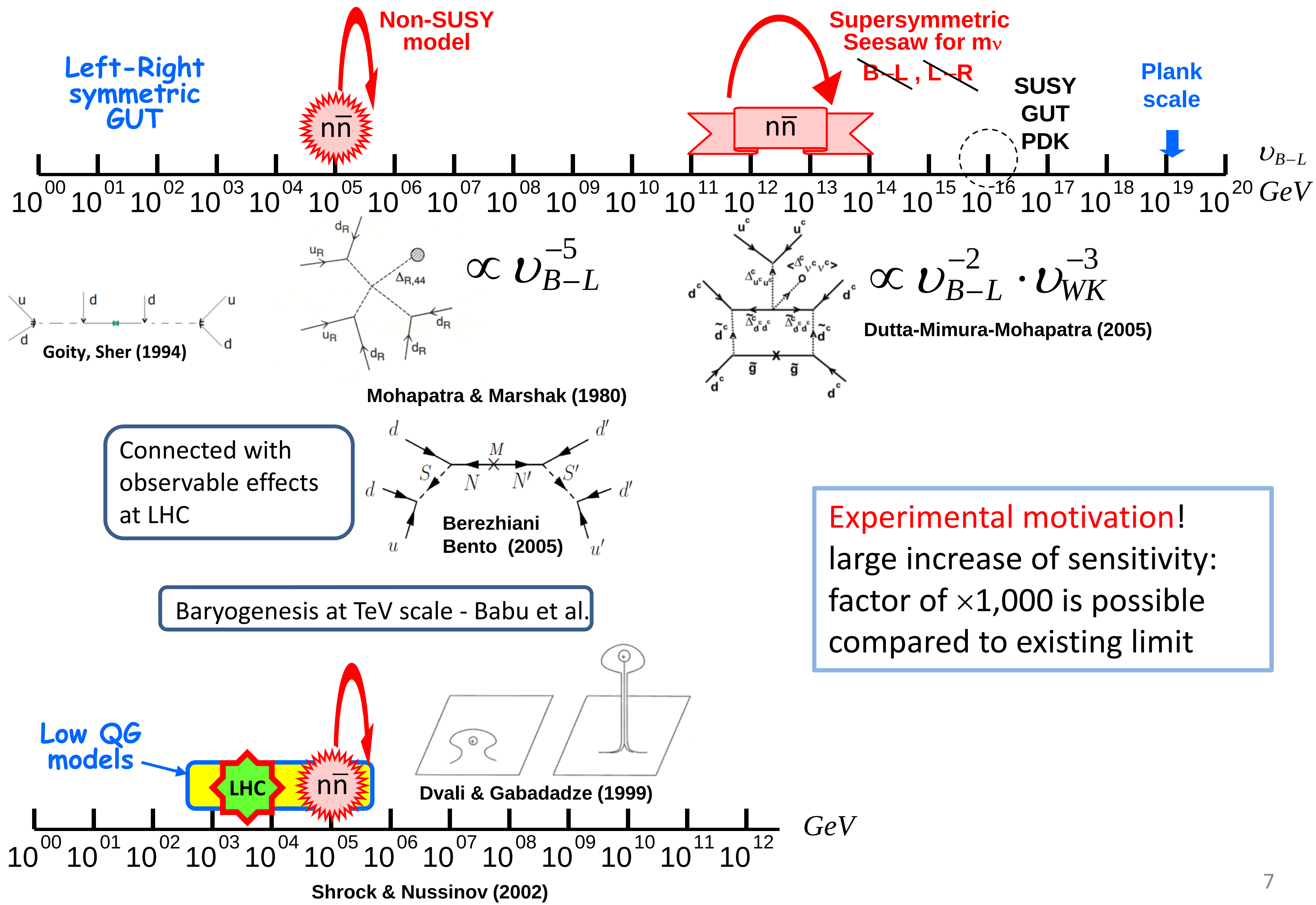
- Alternative search for $n \longrightarrow \overline{n}$ transformation with ΔB = 2 and (B – L)V (Mohapatra et al, … recent Wise et al.)

- All theoretical models with ΔB = 1 and ΔB = 2 at high-energy scale have difficulties when passing through the electroweak period due to sphaleron mechanism.

  → Interesting class of models with baryogenesis below EW scale (Berezhiani, Babu …)

  These models explain small neutrino masses, predict new color scalars at LHC and observable $n \longrightarrow \overline{n}$.

$Scales\ \ of\ \ n \rightarrow \bar{n}\ \ (B-L)V\ \ in\ \ theory$



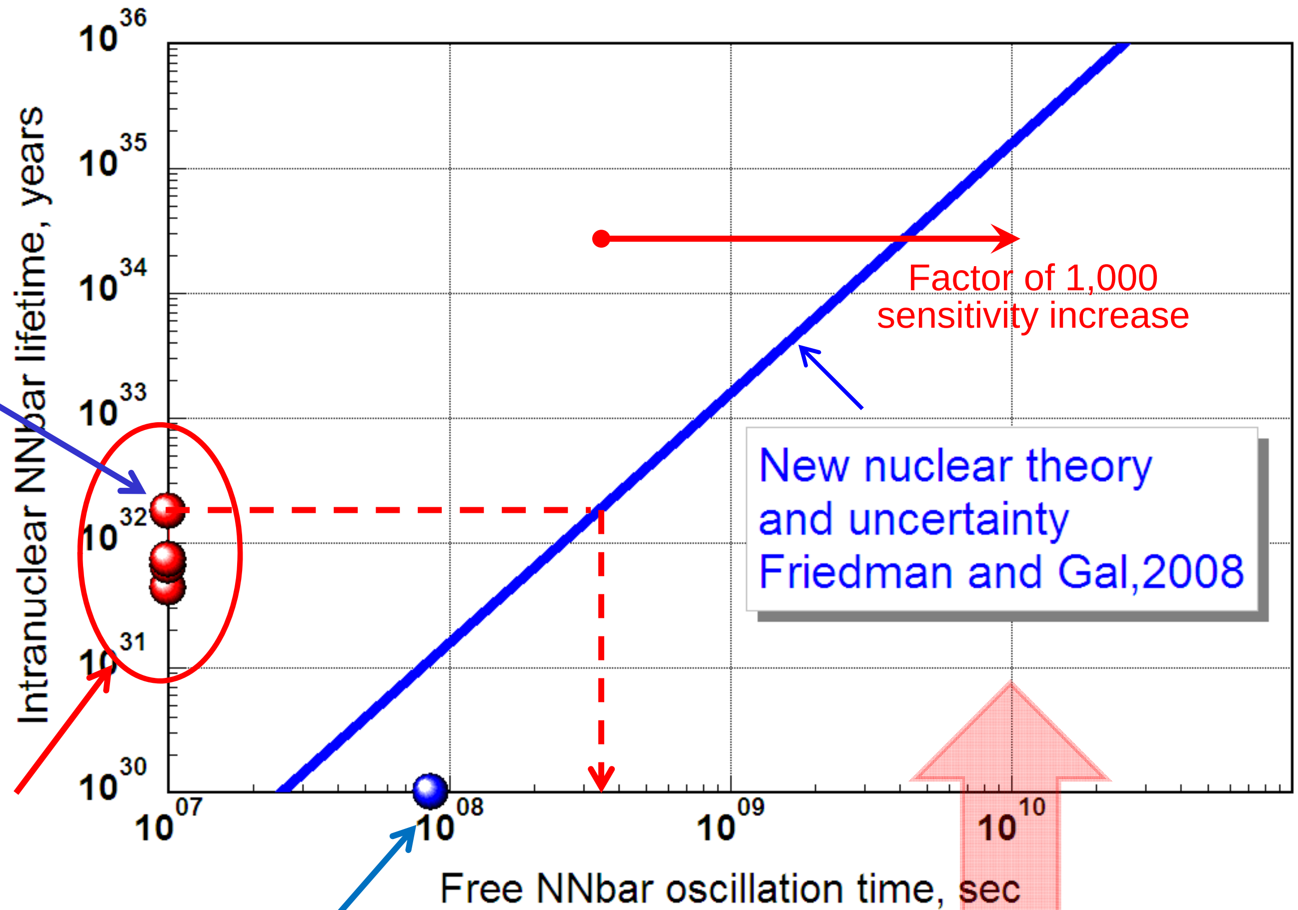
Experimental motivation!
large increase of sensitivity: factor of ×1,000 is possible compared to existing limit

$$\tau_{bound} = R \times \tau_{free}^2$$

Free Neutron and Bound Neutrons NNbar Search Limits Comparison

Large improvement with free-neutron experiments is possible

Recent S-K (2011) limit based on 24 candidates and 24.1 bkgr.

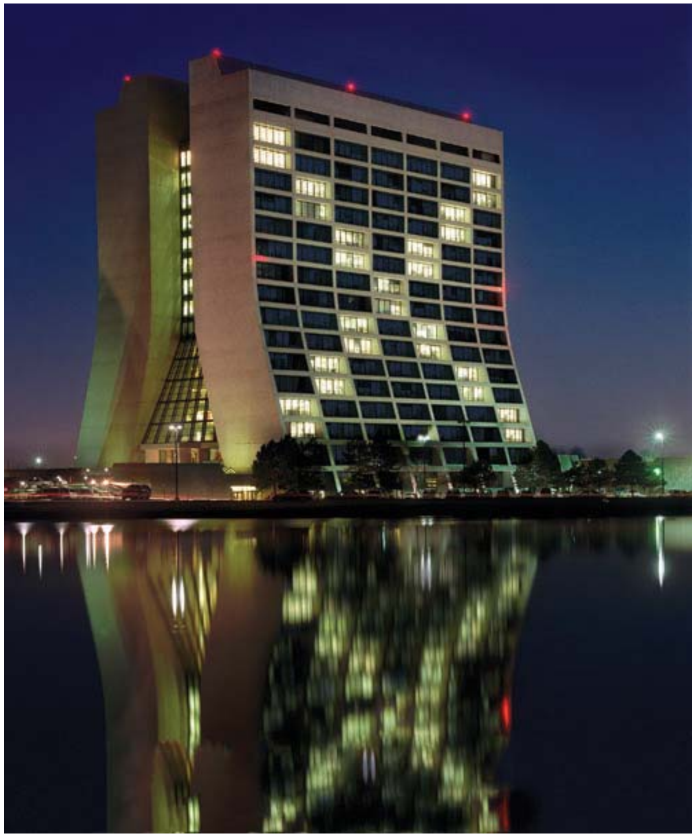


intranuclear search exp. limits: Super-K, Soudan-2 Frejus, SNO

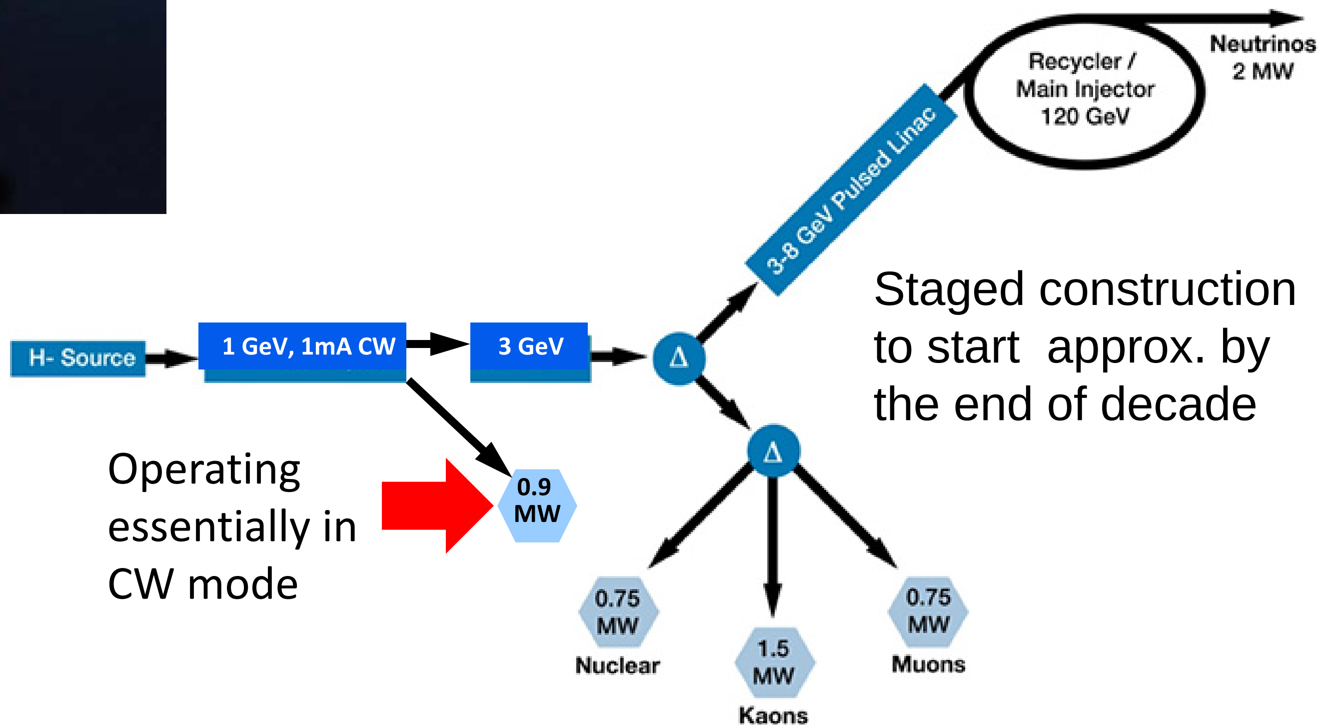
Free neutron search limit (ILL - 1994)

Goal of new NNbarX search with free neutrons

N-spallation target
in Project X
at US HEP Intensity Frontier



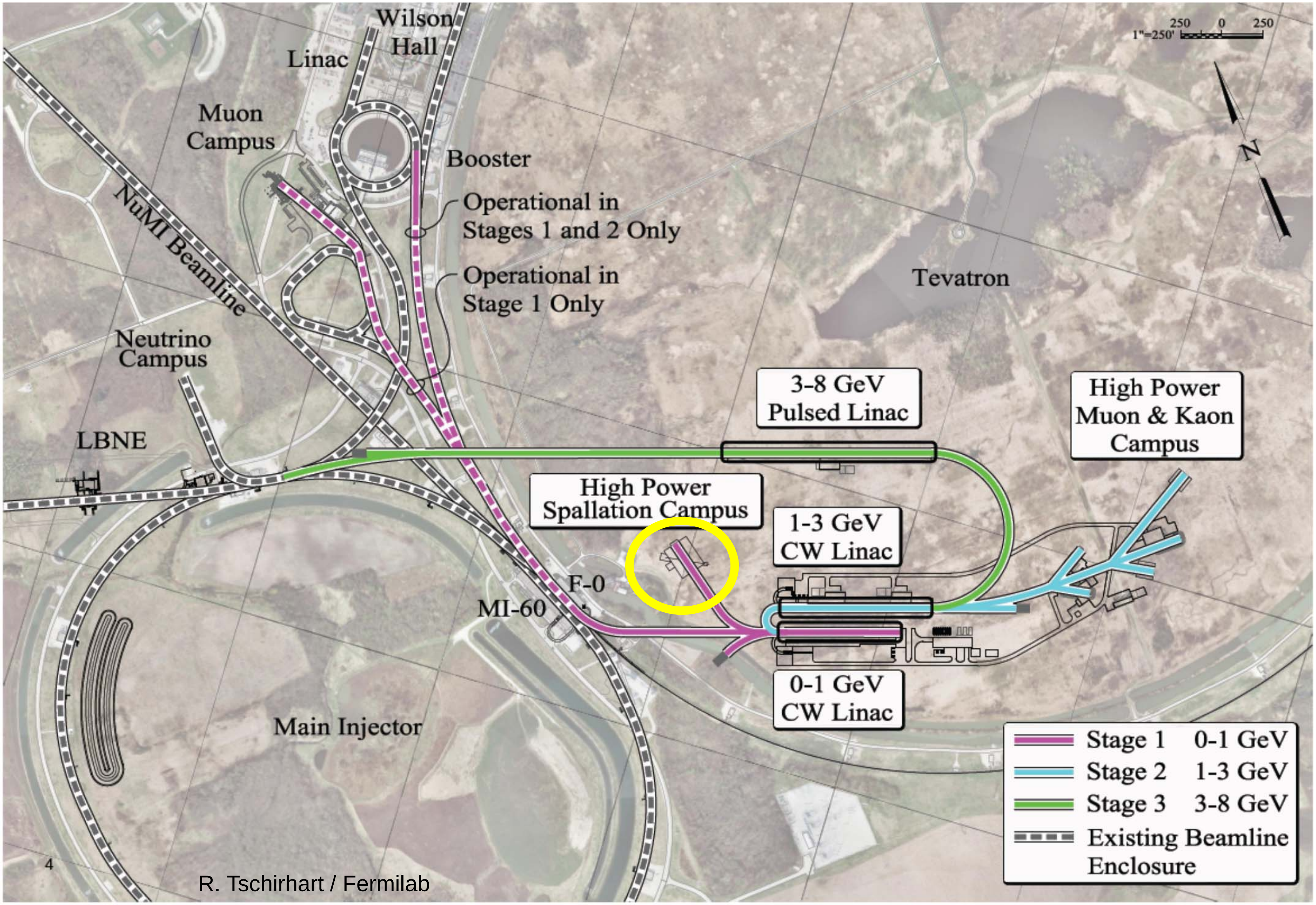
Fermilab



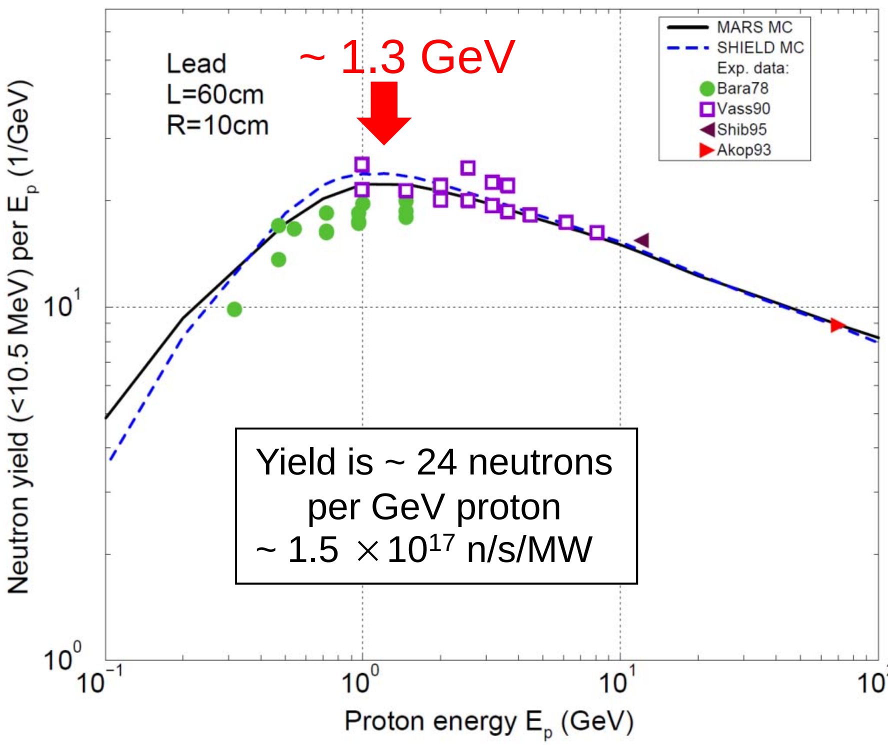
Operating essentially in CW mode

Staged construction to start approx. by the end of decade

Staged Project X (Development state of 2013)



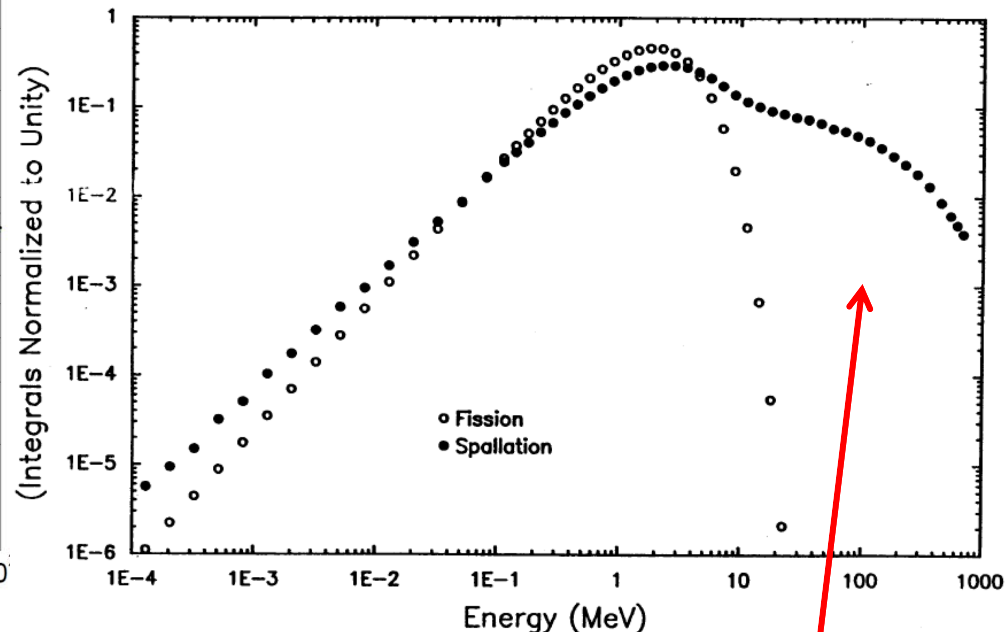
Optimal Neutron Production Energy



N. Mokhov, MARS simulations, FNAL, 2011

For target made of fissionable materials (e.g. Th, DU) neutron yield can be factor ~ 2 higher (geometry dependent)

Spectrum of Primary Neutrons



Spectrum of primary fast n from spallation target and from fission (Courtesy of Gary Russel).

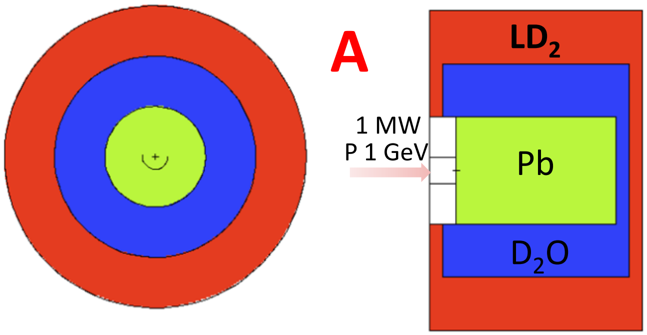
Potential source of the "fast" background for n-nbar that was non-existent in the previous ILL experiment

Primary advantage of Project X neutron source

is that it can be designed and built as a dedicated facility (not as a multi-user facility at the research reactors and other spallation sources) for optimum needs of the fundamental physics experiments: such as n-nbar, n-EDM and possibly some others.

- It will be designed with participation of the physicists – experimentalists who will later use it. Thus, NNbarX members are developing a pre-conceptual spallation target/cold source design.
- To provide long lifetime and moderate cost to the facility the design of the target/source can be modular and <u>reconfigurable.</u>
- CW operation makes cooling/service target requirements easier. Long pulse operation would be helpful for suppression of fast backgrounds. We believe that detector can be made backgroundless as in ILL experiment. N-nbar effect can be suppressed by weak magnetic field.

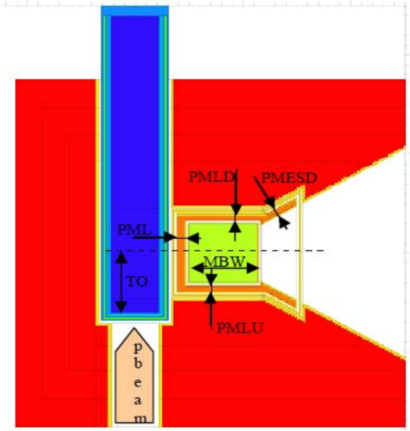
Target Models in MCNPX (to be optimized)

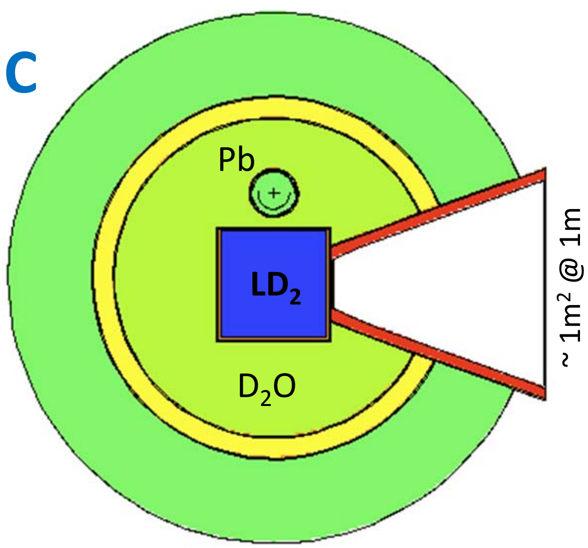


Configuration (A) G. Muhrer/LANL

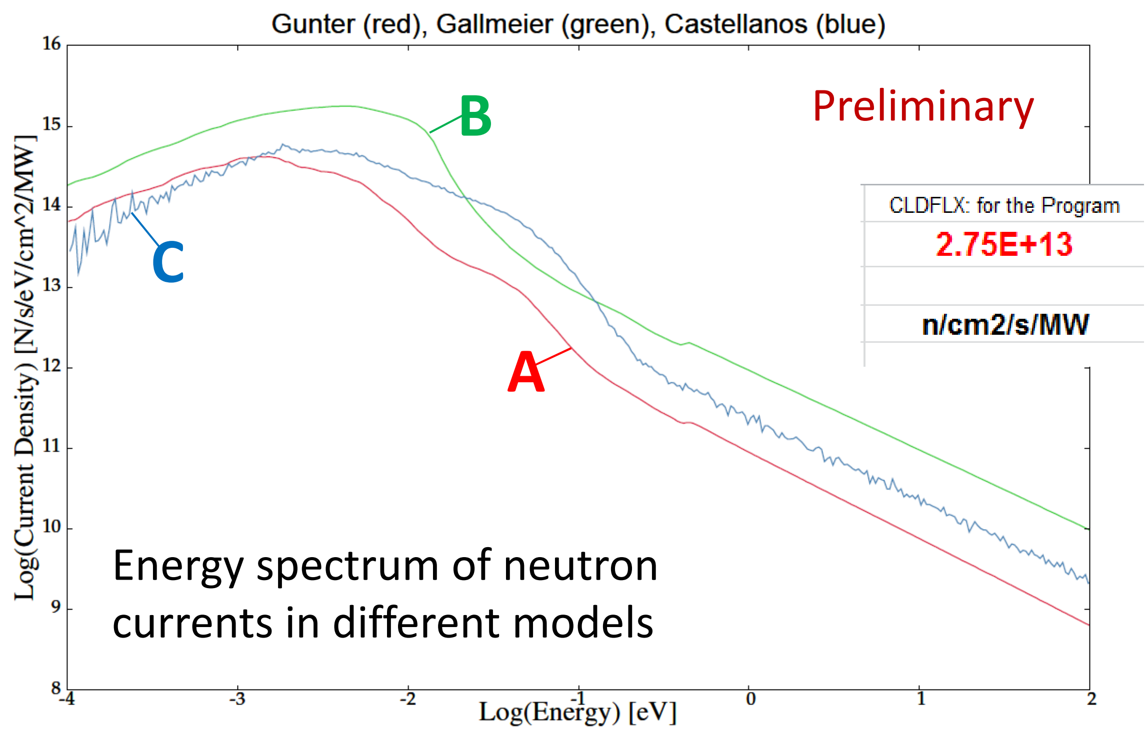
Configuration (B)
F. Gallmeier/SNS

B





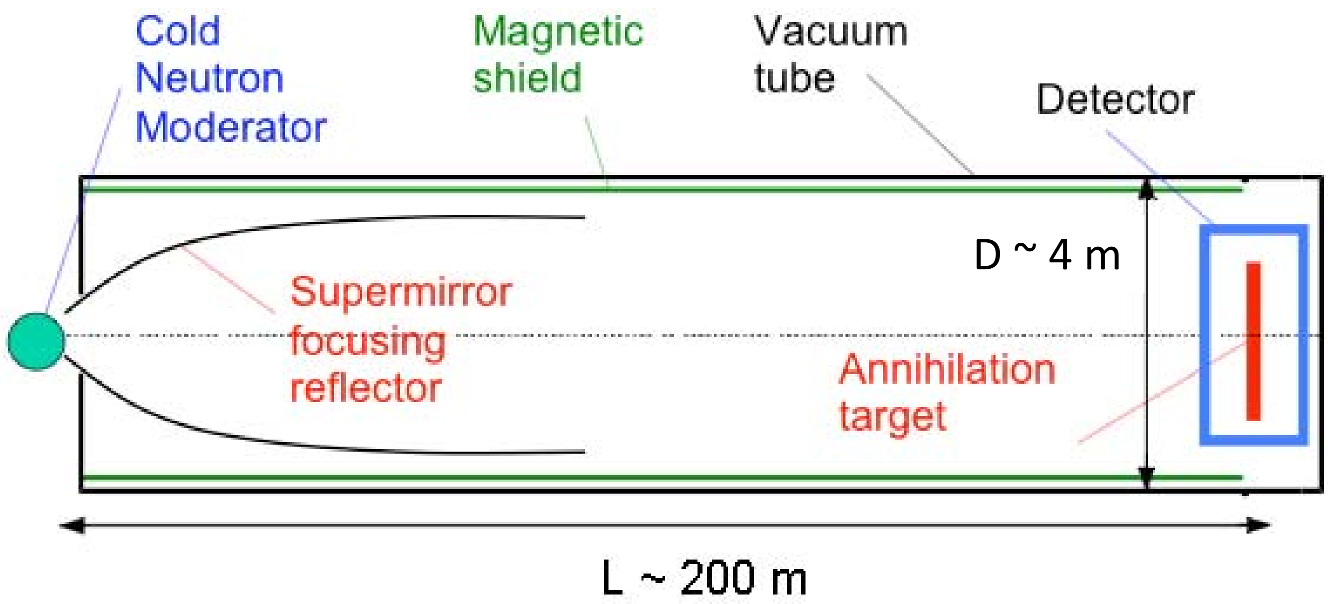
Initial UT model (C) L. Castellanos/UT



Energy spectrum of neutron currents in different models

Conceptual Horizontal Baseline Configuration

with elliptical focusing reflector (method proposed by us in 1995)



<u>Typical initial baseline parameters:</u>

Luminous source area, dia	30 cm
Annihilation target, dia	200 cm
Reflector starts at	2 m
Reflector ends at	50 m
Reflector semi-minor axis	3 m
Distance to target	200 m
Mirror graded m segments	from 7 to 3
Vacuum	$< 10^{-5}$ Pa
Residual magnetic field	< 1 nT

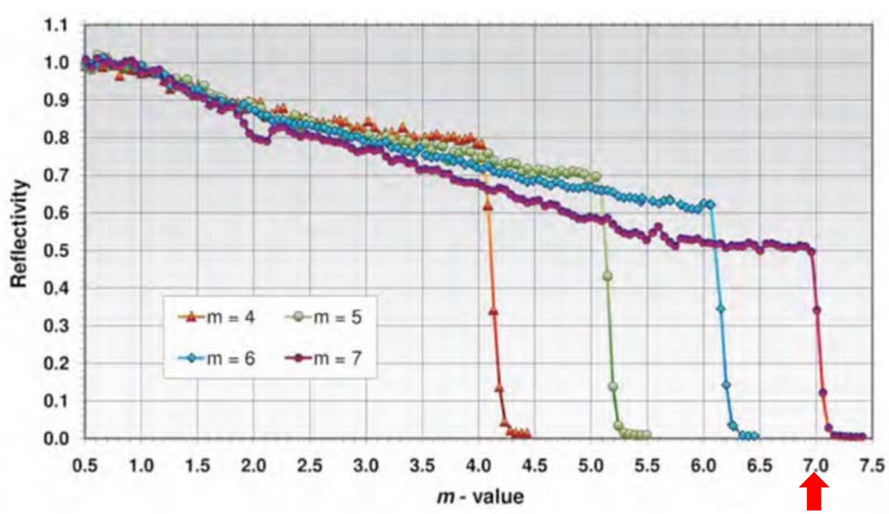
<u>Typical sensitivity Nt^2:</u>

$\gtrsim$ 1,000 “ILL units”

Parameters are subject of optimization by Monte-Carlo including overall cost

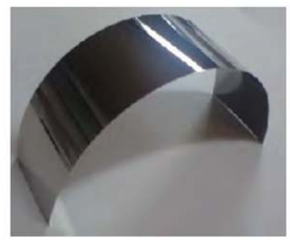
Super-mirrors material for large elliptical focusing reflector

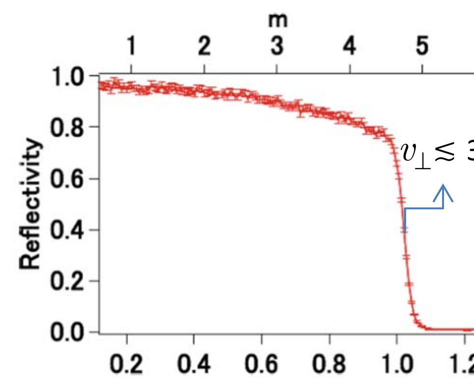
Commercial products of Swiss Neutronics



$v_\perp \lesssim 50$ m/s

Progress in neutron super-mirrors



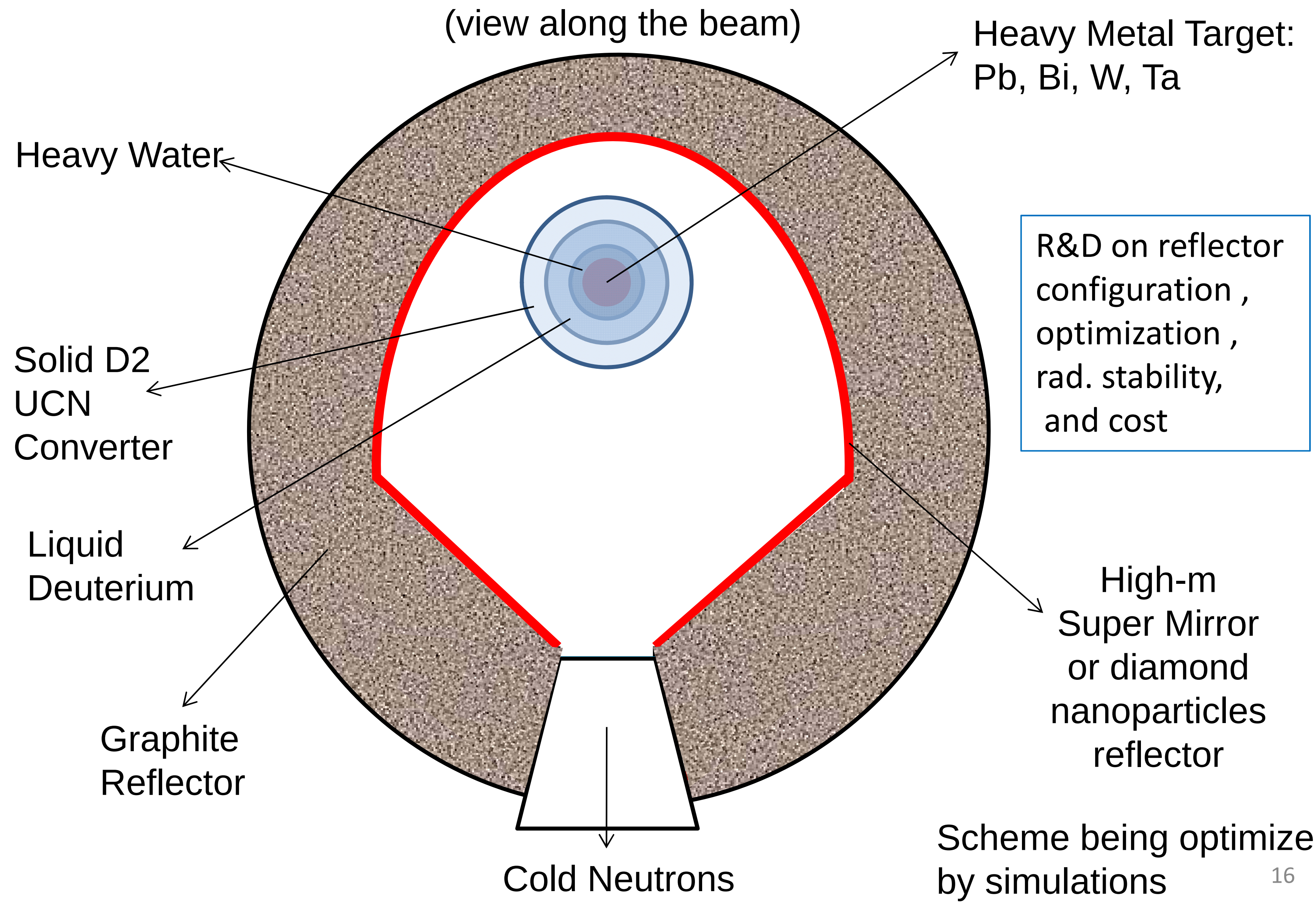


$v_\perp \lesssim 30$ m/s

no substrate (radiation hardness expected)

(H. Shimizu, 2012)

Conceptual dedicated spallation target with VCN-UCN converter (4π emission)



R&D on reflector configuration, optimization, rad. stability, and cost

Scheme being optimized by simulations

R&D studies
on Vertical layout

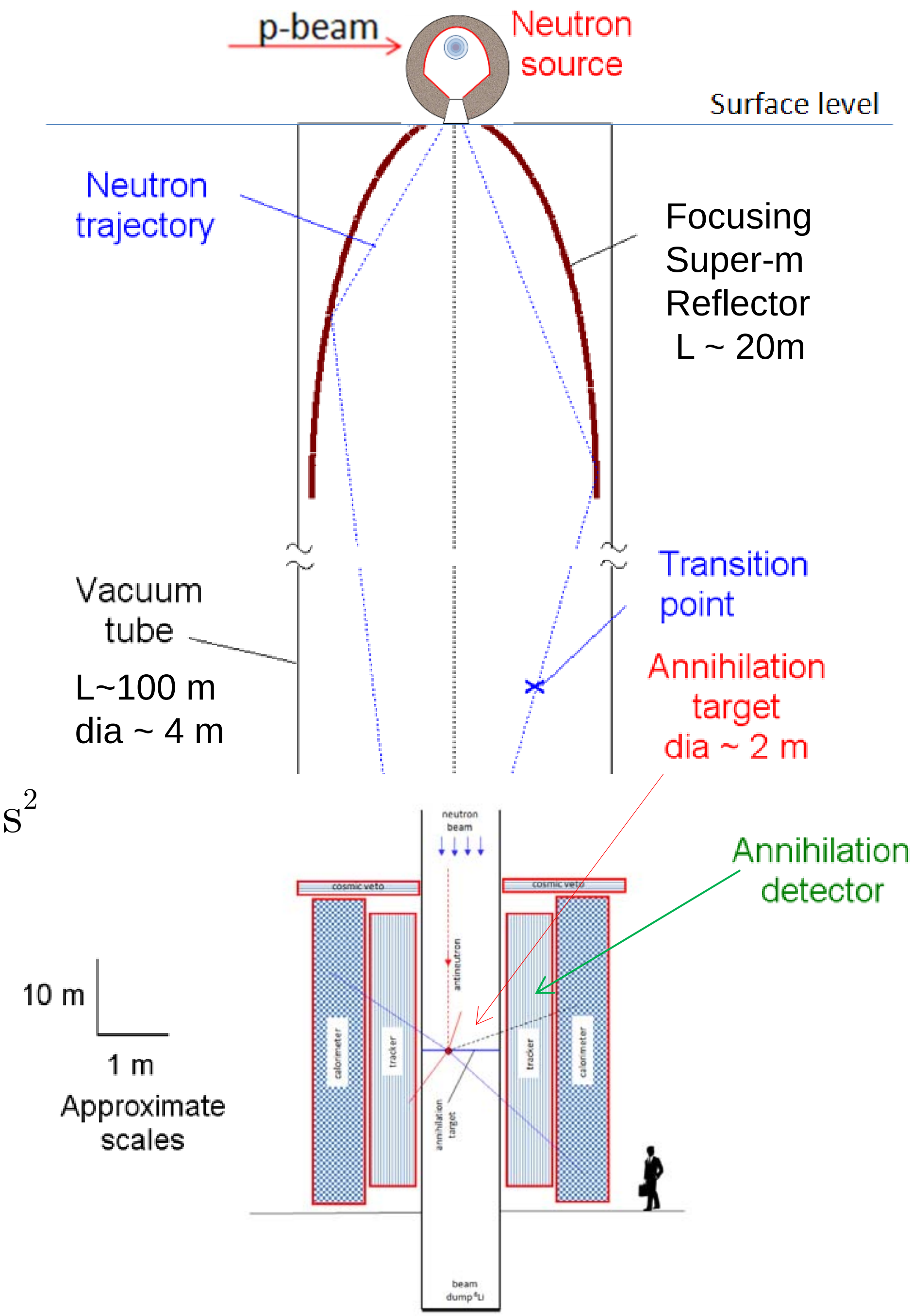
Examples of vertical motion:

$$h = v_0 t + \tfrac{1}{2} g t^2$$

$$105\ \mathrm{m} = 100\ \mathrm{m/s} \cdot 1\ \mathrm{s} + 4.9\ \mathrm{m/s^2} \cdot 1^2 \mathrm{s}^2$$

$$105\ \mathrm{m} = 10\ \mathrm{m/s} \cdot 3.7\ \mathrm{s} + 4.9\ \mathrm{m/s^2} \cdot 3.7^2 \mathrm{s}^2$$

Both VCN and UCN can be used



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journal homepage: www.elsevier.com/locate/nima

The reflection of very cold neutrons from diamond powder nanoparticles

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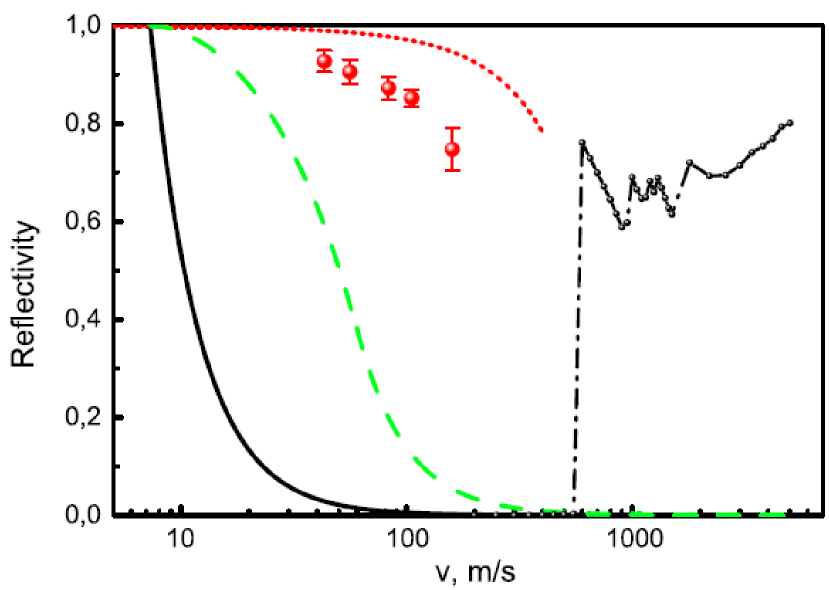
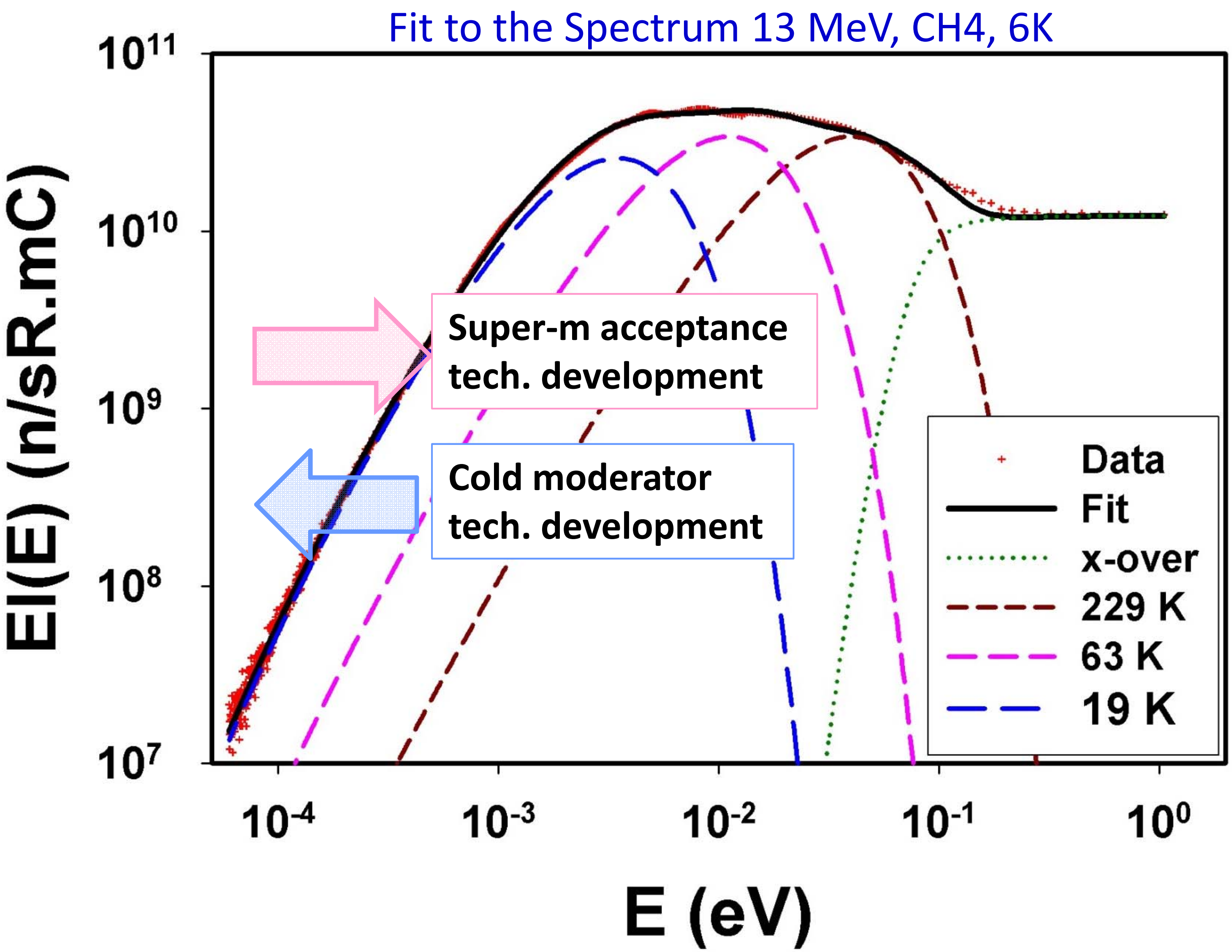


Fig. 9. The elastic reflection probability for isotropic neutron flux is shown as a function of the neutron velocity for various carbon-based reflectors: (1) Diamond-like coating (DLC) (thin solid line), (2) The best supermirror [16] (dashed line), (3) Hydrogen-free ultradiamond [15] powder with the infinite thickness (dotted line). Calculation. (4) VCN reflection from 3 cm thick diamond nanopowder at ambient temperature (points), with significant hydrogen contamination [this Letter]. Experiment. (5) MCNP calculation for reactor graphite reflector [2] with the infinite thickness at ambient temperature.

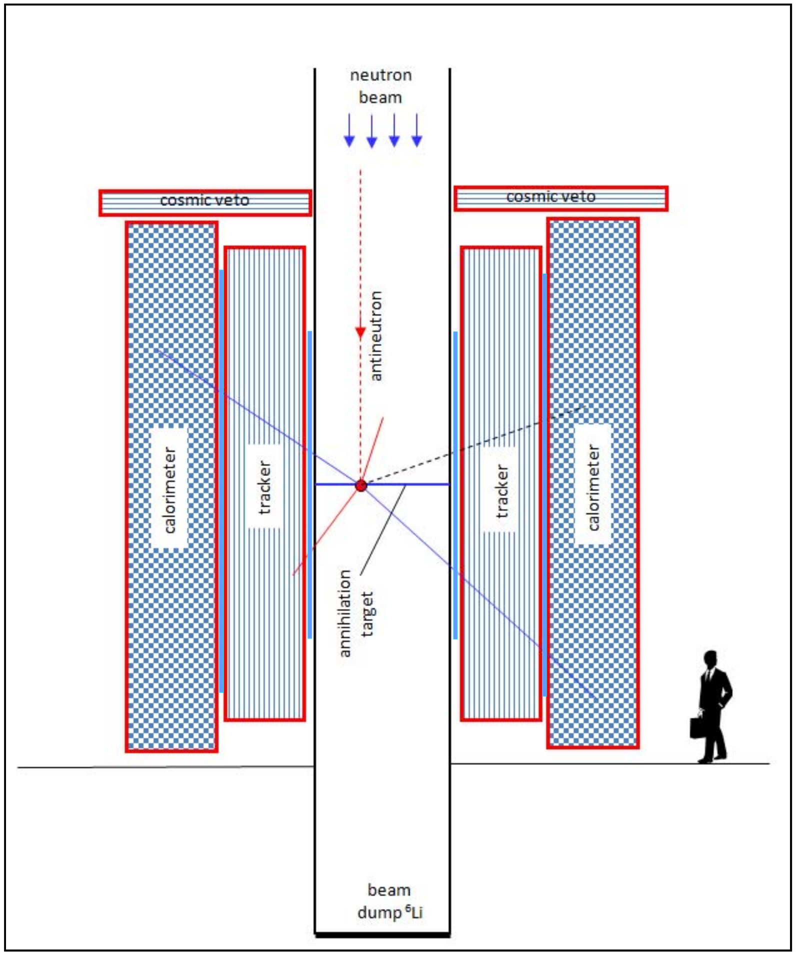
Fig. 4. The VCN trap. The cover is open.

Colder moderator R&D at Indiana University / CEEM



Dave Baxter, Chen-Yu Liu / Indiana U.

Annihilation Detector



Annihilation feature: $\overline{n} + C \rightarrow \langle 5\pi \rangle$

- Use concepts of backgroundless ILL detector;
- Can be Vertical and Horizontal;
- Carbon-film annihilation target;
- Tracker for vertex to thin carbon target;
- Calorimeter for trigger and energy reconstruction;
- TOF before and after tracker to remove vertices of particles coming from outside;
- Cosmic veto;
- Intelligent shielding and beam dump to minimize (n,γ) emission.
- R&D on detector configuration and cost optimization by NCSU, IU, and India together with FNAL

September 4, 2012

Expression of Interest

Search for Neutron-Antineutron Transformation at Fermilab

The NNbarX Collaboration

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- HEP and NP groups from US Universities are involved together with Fermilab
- National Labs neutron and spallation target experts are engaged
- International groups and experts participate
- Strong Theory Support group:
  K. Babu, Z. Berezhiani,
  M-C. Chen, R. Cowsik,
  A. Dolgov, A. Gal, B. Kerbikov,
  B. Kopeliovich, V. Kopeliovich,
  R. Mohapatra, L. Okun, C. Quigg,
  U. Sarkar, R. Shrock, A. Vainshtein

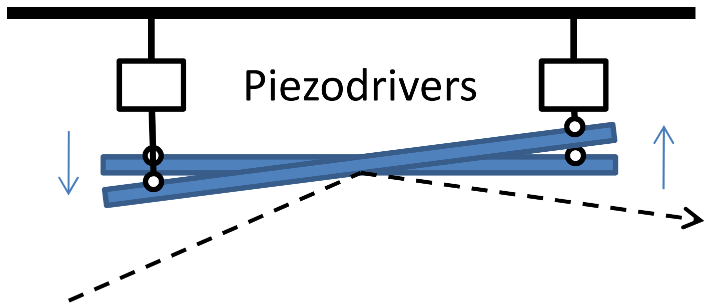
Summary

- With existing super-mirror technology high sensitivity increase for n-nbar is possible > 1,000 in “ILL units” restricted by practical cost consideration.
- With 4π emission, source reflector, and vertical experiment layout further increase of sensitivity can be possible to be explored by R&D work.
- Sensitivity increase by factor $10^3 – 10^4$ in “ILL units” would be required according to some theoretical models with observable n-nbar. Theoretical significance of n-nbar observation is very high.
- With backgroundless detector single observed event can be a discovery. Positive observation can be uniquely cross-checked with magnetic field suppression.
- If n-nbar is observed, CPT symmetry can be tested with unprecedented accuracy through equality of neutron and antineutron mass (L. Okun)
- Enhancement of CN production around 9Å can be used for a new n-EDM search operating in parallel with the search of n-nbar.
- Pulsed source operation is feasible for n-nbar search, although not critical except possibly for additional background suppression.
- If n-nbar will not be found within the reach of improved experimental sensitivity the experiment will set a new limit on the stability of matter exceeding the sensitivity of XL nucleon decay experiments. Will test or constraint models of low scale baryogenesis.

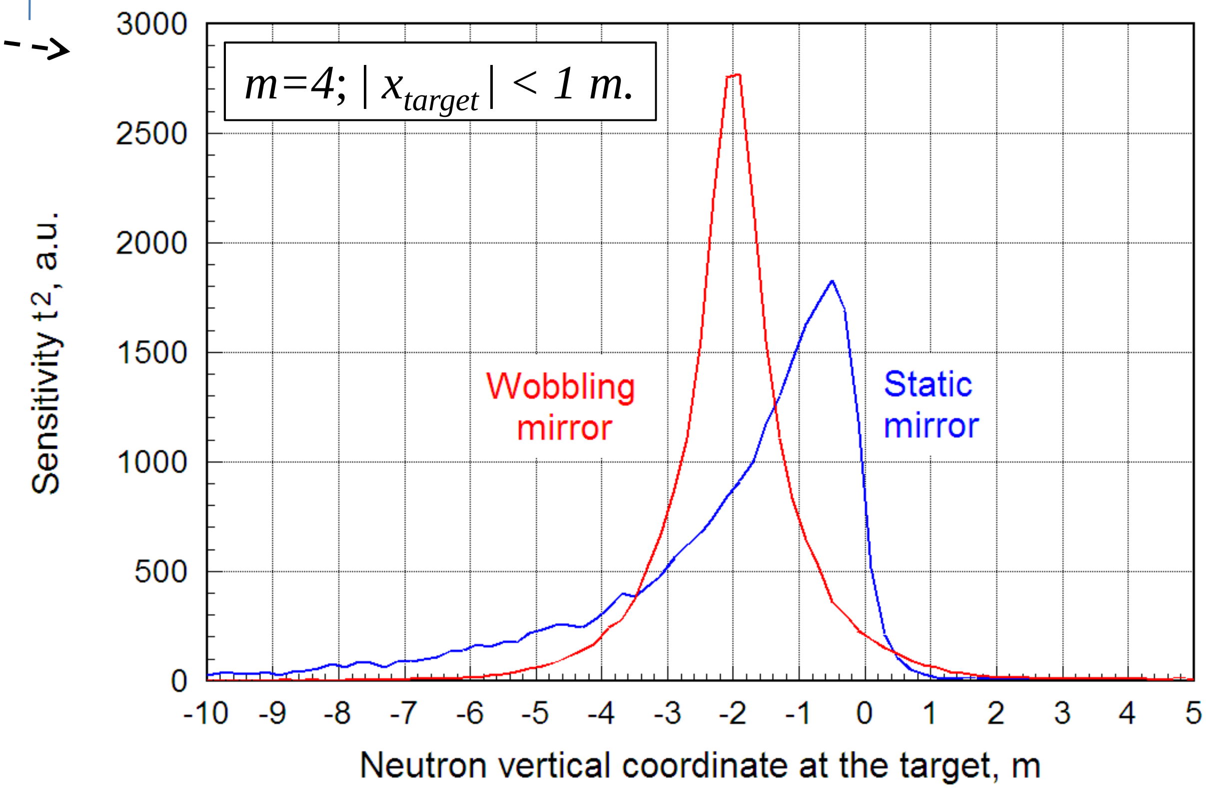
Wobbling super-mirror reflector for pulsed spallation source

(G. Greene, YK, W. M. Snow, and C. Tate, 2009)

Wobbling angle is function of time (velocity) that provides optimum neutron direction



Can be made working.
Not very efficient for n-nbar.
Might useful for other applications at ESS



END

Example Research Program, definitive space of accelerator parameters on Project X website

← Project X Campaign →

Program:	Onset of NOvA operations in 2013	Stage-1: 1 GeV CW Linac driving Booster & Muon, n/edm programs	Stage-2: Upgrade to 3 GeV CW Linac	Stage-3: Project X RDR	Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW
MI neutrinos	470-700 kW**	515-1200 kW**	1200 kW	2450 kW	2450-4000 kW
8 GeV Neutrinos	15 kW +0-50kW**	0-42 kW* + 0-90 kW**	0-84 kW*	0-172 kW*	3000 kW
8 GeV Muon program e.g, (g-2), Mu2e-1	20 kW	0-20 kW*	0-20 kW*	0-172 kW*	1000 kW
1-3 GeV Muon program, e.g. Mu2e-2	-----	80 kW	1000 kW	1000 kW	1000 kW
Kaon Program	0-30 kW** (<30% df from MI)	0-75 kW** (<45% df from MI)	1100 kW	1870 kW	1870 kW
Nuclear edm ISOL program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Cold and Ultra-cold neutron program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Nuclear technology applications	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
# Programs:	4	8	8	8	8
Total max power:	735 kW	2222 kW	4284 kW	6492 kW	11870kW

* Operating point in range depends on MI energy for neutrinos.

** Operating point in range depends on MI injector slow-spill duty factor (df) for kaon program.