A Neutron-Antineutron Oscillation Experiment at Project X Using a Slow Neutron Beam

W. M. Snow
Indiana University/CEEM
ANL Intensity Frontier Workshop

Neutron-antineutron oscillations in nuclei

Free neutron oscillations

Sources of Improvement for a (much) better free neutron experiment

Thanks for slides: Tony Mann, Yuri Kamyshkov, Ed Kearns,…

$n \leftrightarrow \bar{n}$ oscillations — can we add them to the list?

Neutral meson $|q\bar{q}\rangle$ states oscillate -

$$K^0, B^0 \longleftrightarrow \left(2^{nd} \text{ order weak} \right) \longleftrightarrow \overline{K^0}, \overline{B^0}$$

And neutral fermions can oscillate too -

$$\nu_\mu \longleftrightarrow \left(\cdots \right) \longleftrightarrow \nu_e$$

So why not -

$$n \longleftrightarrow \left(\text{New physics} \right) \longleftrightarrow \bar{n} \qquad ?$$

Neutron is a long-lived neutral particle ($q_n < 10^{-21} e$) and can oscillate into an antineutron. No oscillations have been seen yet.

Need interaction beyond the Standard Model that violates Baryon number (B) by 2 units. No experimental observation of B violation yet. But we expect B violation at some level (see earlier talks)

B,L are Probably Not Conserved

No evidence that either B or L is locally conserved like Q: where is the macroscopic B/L force? (not seen in equivalence principle tests).

Baryon Asymmetry of Universe (BAU) is not zero. If B(t=after inflation)<<BAU (otherwise inflation is destroyed, Dolgov/Zeldovich), we need B violation.

Both B and L conservation are “accidental” global symmetries: given $SU(3)\otimes SU(2)\otimes U(1)$ gauge theory and matter content, no dimension-4 term in Standard Model Lagrangian violates B or L in perturbation theory.

Nonperturbative EW gauge field fluctuations (sphaelerons) present in SM, VIOLATE B, L, B+L, but conserve B-L. Very important process for trying to understand the physics of the baryon asymmetry in the early universe

How to search for B violation experimentally?

Neutron-Antineutron Oscillations: Formalism

$\alpha \neq 0$ allows oscillations

$\Psi = \begin{pmatrix} n \\ \bar{n} \end{pmatrix}$ n-nbar state vector

$\mathrm{H} = \begin{pmatrix} E_n & \alpha \\ \alpha & E_{\bar{n}} \end{pmatrix}$ Hamiltonian of n-nbar system

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

Note :

- α real (assuming T)
- $m_n = m_{\bar{n}}$ (assuming CPT)
- $U_n \neq U_{\bar{n}}$ in matter and in external B [$\mu(\bar{n}) = -\mu(n)$ from CPT]

Neutron-Antineutron transition probability

For $H = \begin{pmatrix} E+V & \alpha \\ \alpha & E-V \end{pmatrix}$ $\qquad P_{n\to\bar{n}}(t) = \frac{\alpha^2}{\alpha^2+V^2} \times \sin^2\left[\frac{\sqrt{\alpha^2+V^2}}{\hbar}t\right]$

where V is the potential difference for neutron and anti-neutron.

Present limit on $\alpha \leq 10^{-23} eV$

Contributions to V:

<Vmatter> ~100 neV, proportional to matter density

<Vmag>=μB, ~60 neV/Tesla; B~10nT-> Vmag~10^{-15} eV

<Vmatter> , <Vmag> both >>α

For $\left[\frac{\sqrt{\alpha^2+V^2}}{\hbar}t\right] << 1$ ("quasifree condition") $\qquad P_{n\to\bar{n}} = \left(\frac{\alpha}{\hbar}\times t\right)^2 = \left(\frac{t}{\tau_{n\bar{n}}}\right)^2$

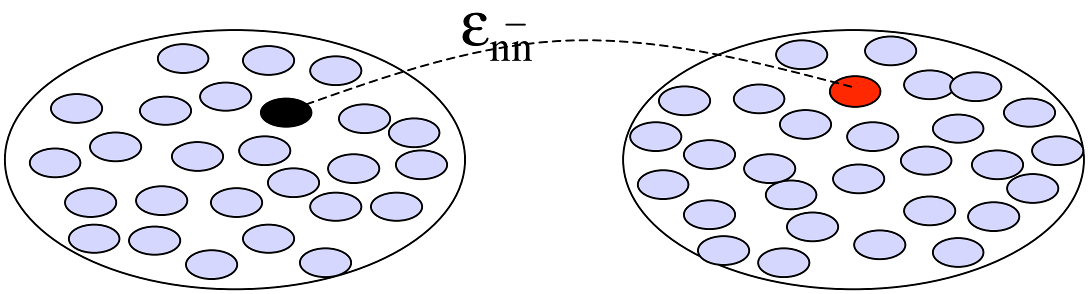
Figure of merit= NT^2 N=#neutrons, T="quasifree" observation time

How to Search for N-Nbar Oscillations

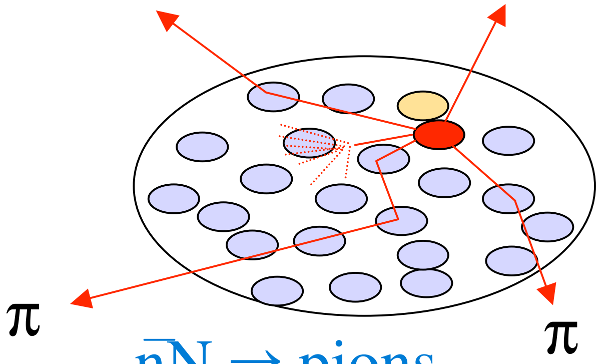
Figure of merit for probability: NT^2
N=total # of free neutrons observed
T= observation time per neutron while in “quasifree” condition

When neutrons are in matter or in nucleus, n-nbar potential difference is large->quasifree observation time is short
B field must be suppressed to maintain quasifree condition due to opposite magnetic moments for neutron and antineutron

(1) n-nbar transitions in nuclei in underground detectors
(2) Cold and Ultracold neutrons



Nucleus $A \rightarrow A^* + \bar{n}$



$\bar{n}N \rightarrow$ pions

Vacuum N-Nbar transformation from bound neutrons:

Best result so far from Super-K in Oxygen-16

$$\boxed{\tau_{^{16}O} > 1.89 \leftrightarrow 10^{32}\, yr \quad (90\% \text{ CL})}$$

ℜ 24 observed candidates;
24.1 exp. background

$$\boxed{\tau_{nucl} = R \times \tau^2_{n\bar{n}\ \text{free}}}$$

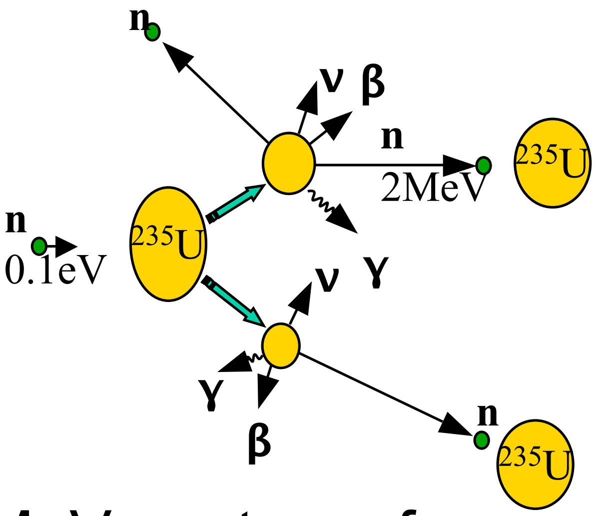
if $R_{^{16}O} = 5 \cdot 10^{22}\, s^{-1}$ (from Friedman and Gal 2008)

$$\Rightarrow \tau(\text{from bound}) > 3.5 \times 10^8\, s \quad \text{or} \quad \alpha < 2 \times 10^{-24}\, eV$$

↔16 times higher than
sensitivity of ILL expt.

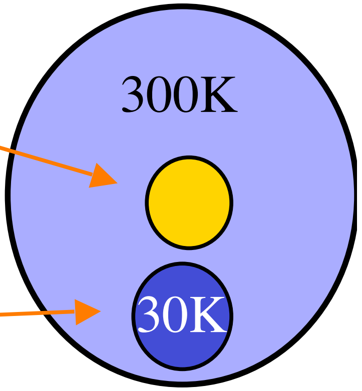
ILL limit (1994) for free neutrons: $\tau_{n\bar{n}} > 0.86 \times 10^8\, s$

“Slow” Neutrons: MeV to neV



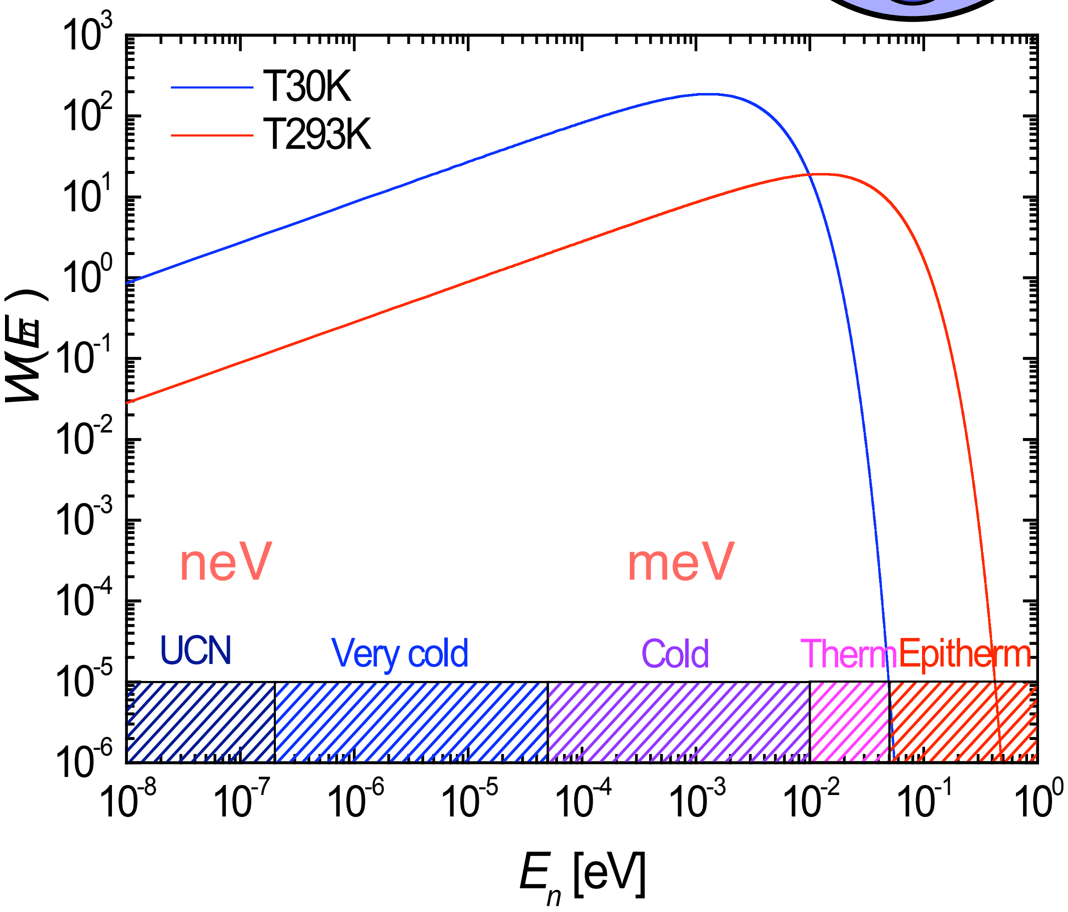
~MeV neutrons from fission or spallation, thermalized in ~ 20 collisions in ~ 100 μs

T (K)	E (meV)	λ (A)	v (m/sec)
300	25	1.6	2200
20	2	6.4	550

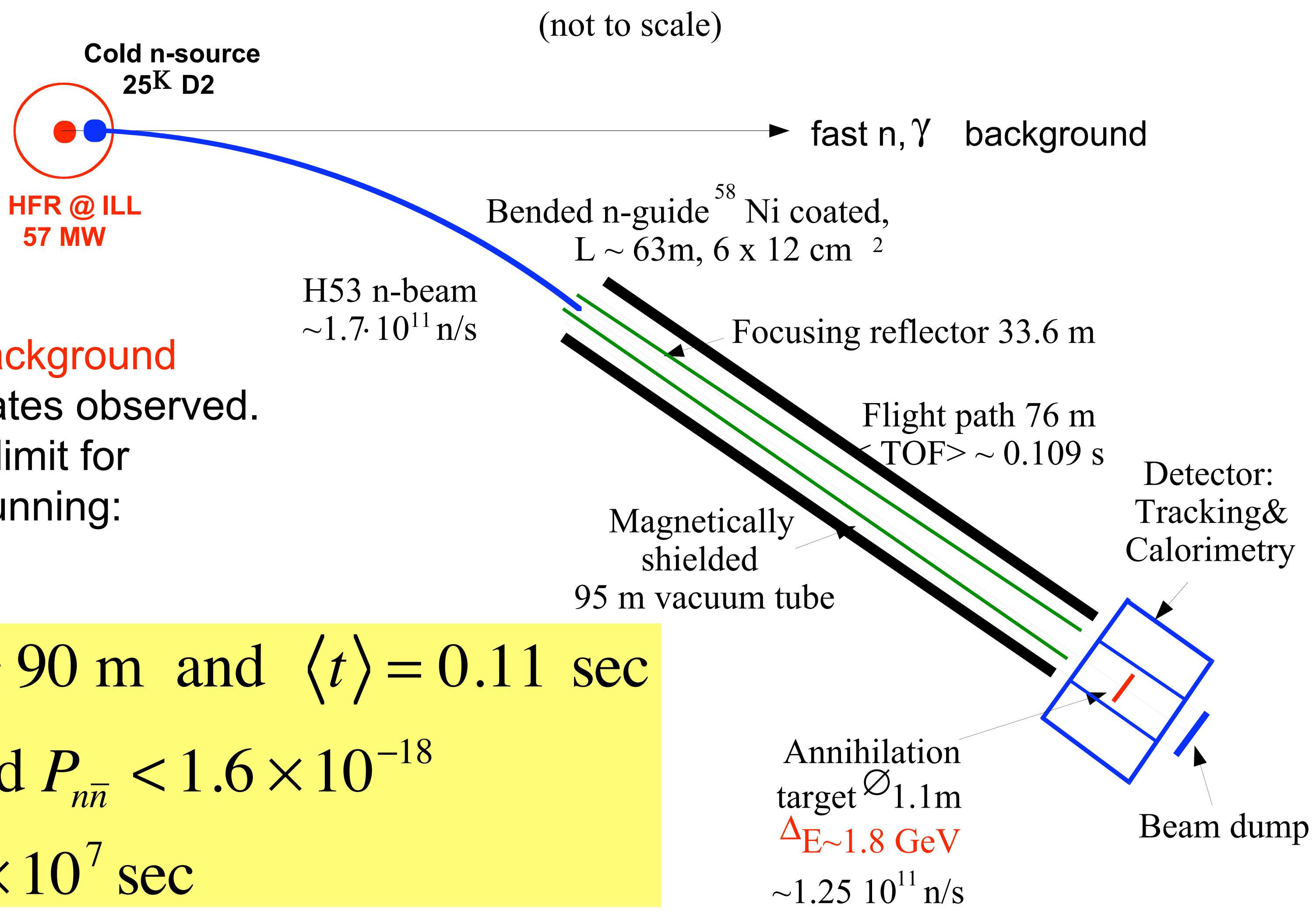


Nuclear reactor/ Spallation source

Neutron Moderator (LH2, LD2)



N-Nbar search at ILL (Heidelberg-ILL-Padova-Pavia)



(not to scale)

Cold n-source
25^{K} D2

HFR @ ILL
57 MW

fast n, γ background

Bended n-guide ^{58}Ni coated,
L ~ 63m, 6 x 12 cm ^{2}

H53 n-beam
$\sim 1.7 \cdot 10^{11}$ n/s

Focusing reflector 33.6 m

Flight path 76 m
<TOF> ~ 0.109 s

Magnetically
shielded
95 m vacuum tube

Detector:
Tracking&
Calorimetry

Annihilation
target $\varnothing$1.1m
ΔE~1.8 GeV

$\sim 1.25\ 10^{11}$ n/s

Beam dump

No GeV background
No candidates observed.
Measured limit for
a year of running:

$$\text{with L} \sim 90\text{ m and } \langle t \rangle = 0.11\text{ sec}$$

$$\text{measured } P_{n\bar{n}} < 1.6 \times 10^{-18}$$

$$\tau > 8.6 \times 10^{7}\text{ sec}$$

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

Quasifree Condition: B Shielding and Vacuum

$\mu B t << \hbar$ ILL achieved |B|<10 nT over 1m diameter, 80 m beam,one layer 1mm shield in SS vacuum tank, 1% reduction in oscillation efficiency (Bitter et al, NIM A309, 521 (1991). For new experiment need |B|<~1 nT

If nnbar candidate signal seen, easy to "turn it off" by increasing B

$V_{opt} t << \hbar$:

Need vacuum to eliminate neutron-antineutron optical potential difference.

$P<10^{-5}$ Pa is good enough, much less stringent than LIGO

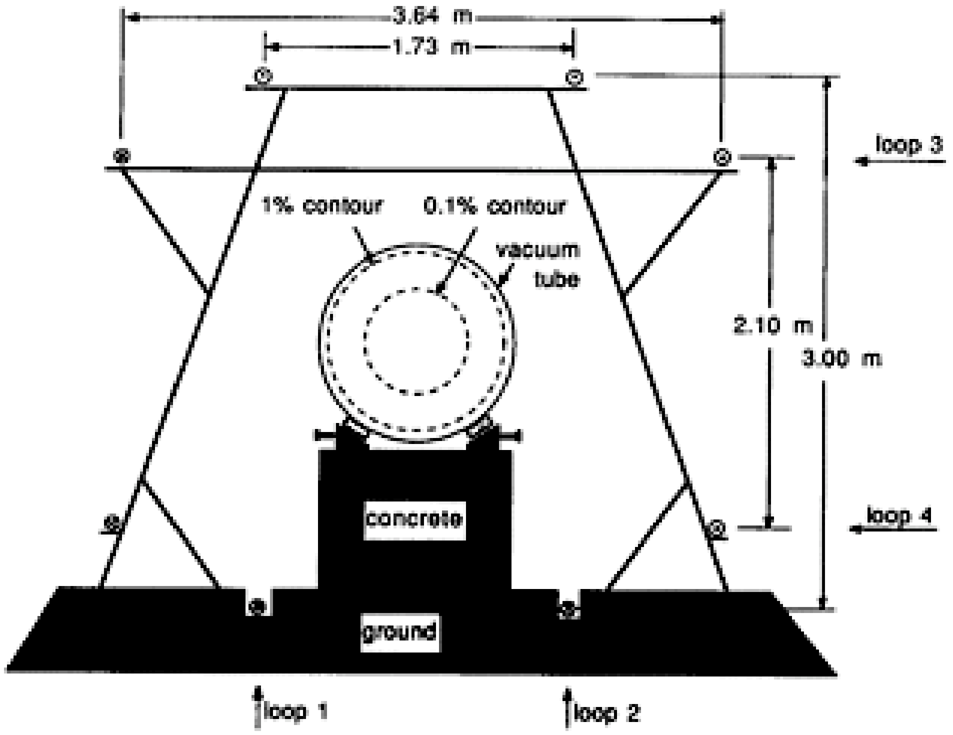
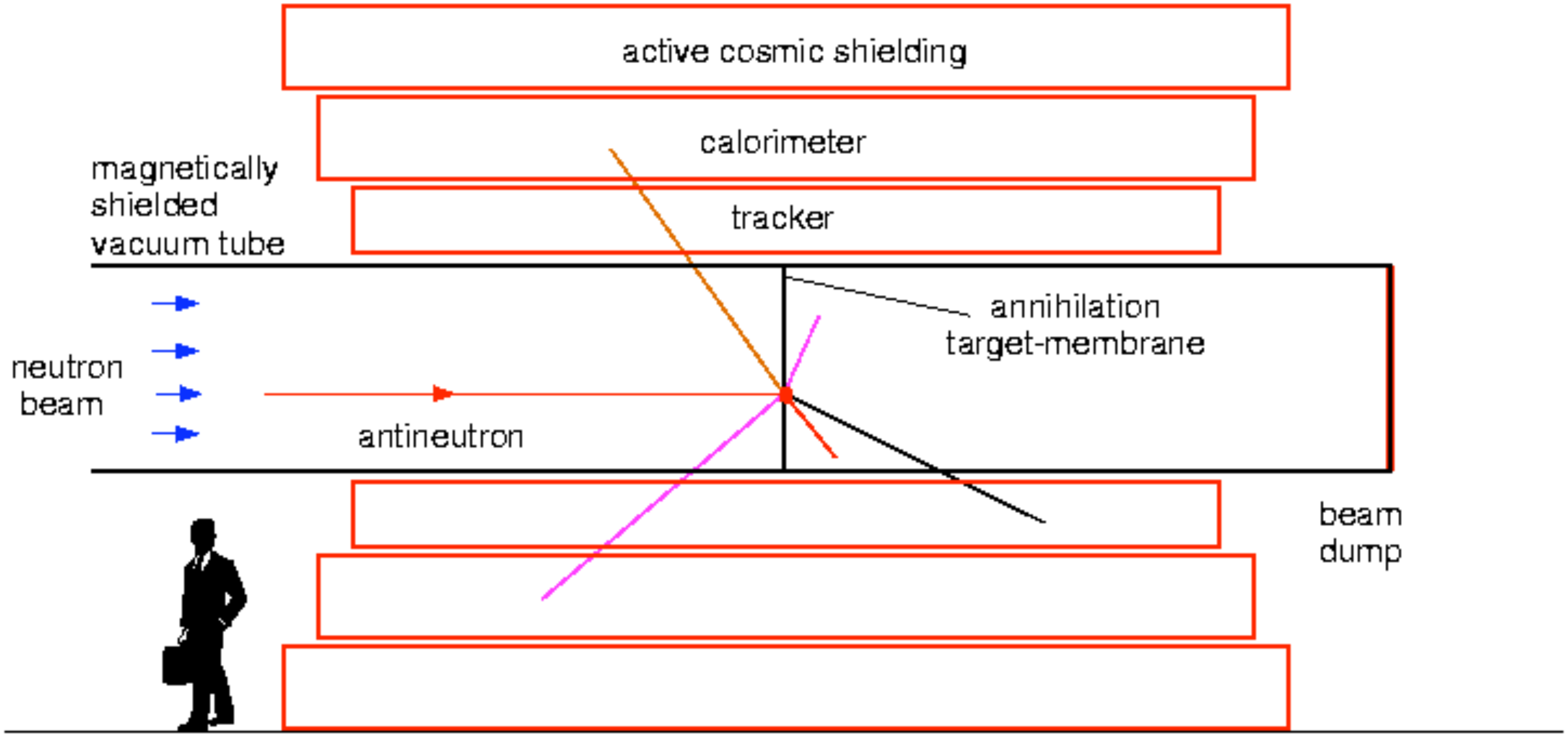


Fig. 10. The transverse field compensation system. Loops 1 and 2 are under 49 A current and compensate the horizontal field component; loops 3 and 4 are under 120 A current and compensate the vertical field component.

The conceptual scheme of antineutron detector



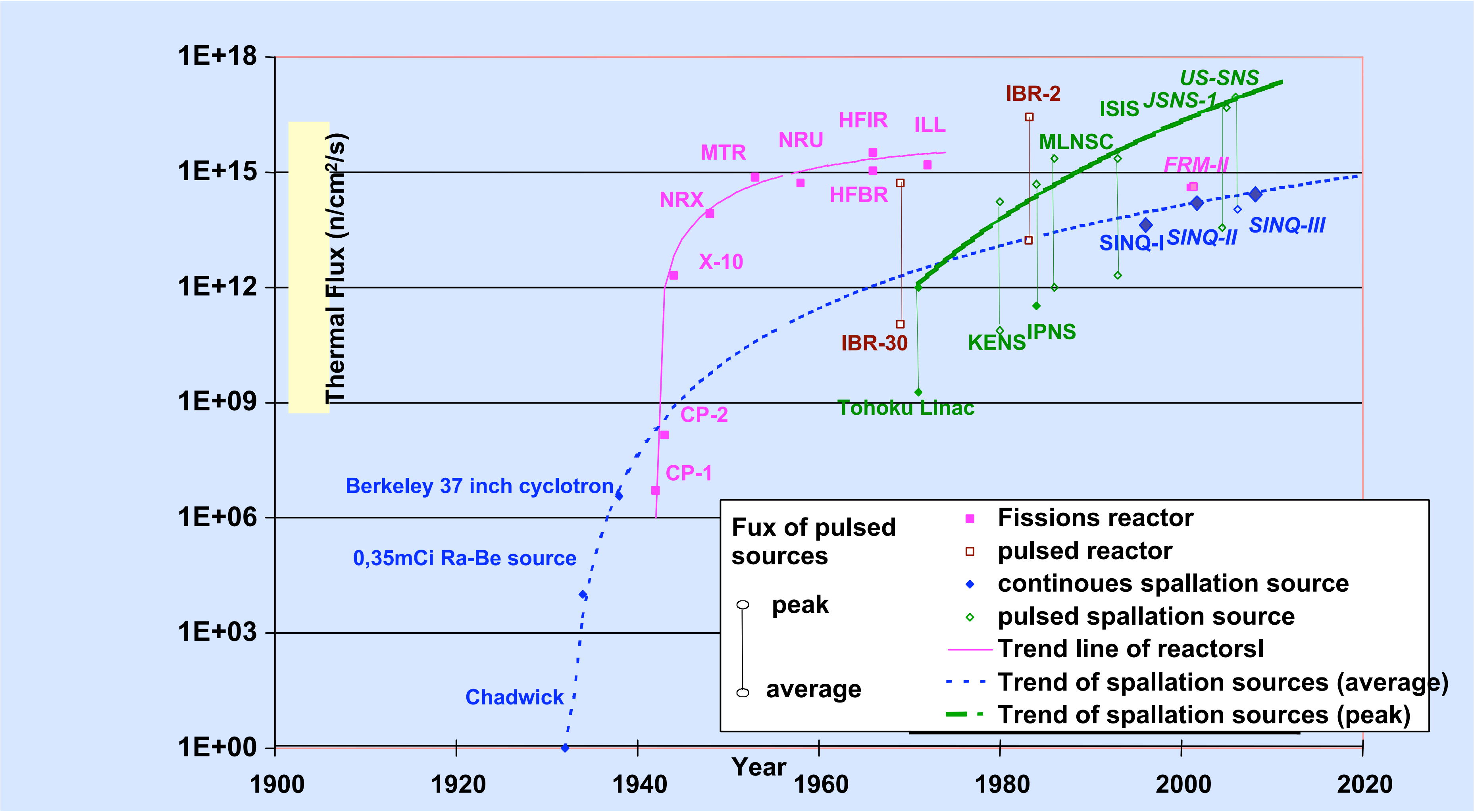
$$\boxed{\bar{n} + A \rightarrow \langle 5 \rangle \; pions \quad (1.8\ \mathrm{GeV})}$$

Annihilation target: ~100μ thick Carbon film

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

vertex precisely defined. No background was observed

How to Improve the Experiment?
Max neutron flux/brightness: ~unchanged for ~4 decades



Neutron flux is increasing only slowly with time

R. Eichler, PSI

Better Slow Neutron Experiment: What do we want? (HOW DIFFICULT IS IT?)

While still keeping quasifree condition, one wants more NT^2 with nbar detector watching the annihilation surface

- higher cold neutron brightness from source POSSIBLE

- slower cold neutron energy spectrum DIFFICULT

- more efficient extraction of cold neutrons with optics to quasifree flight/detector GREAT PROGRESS

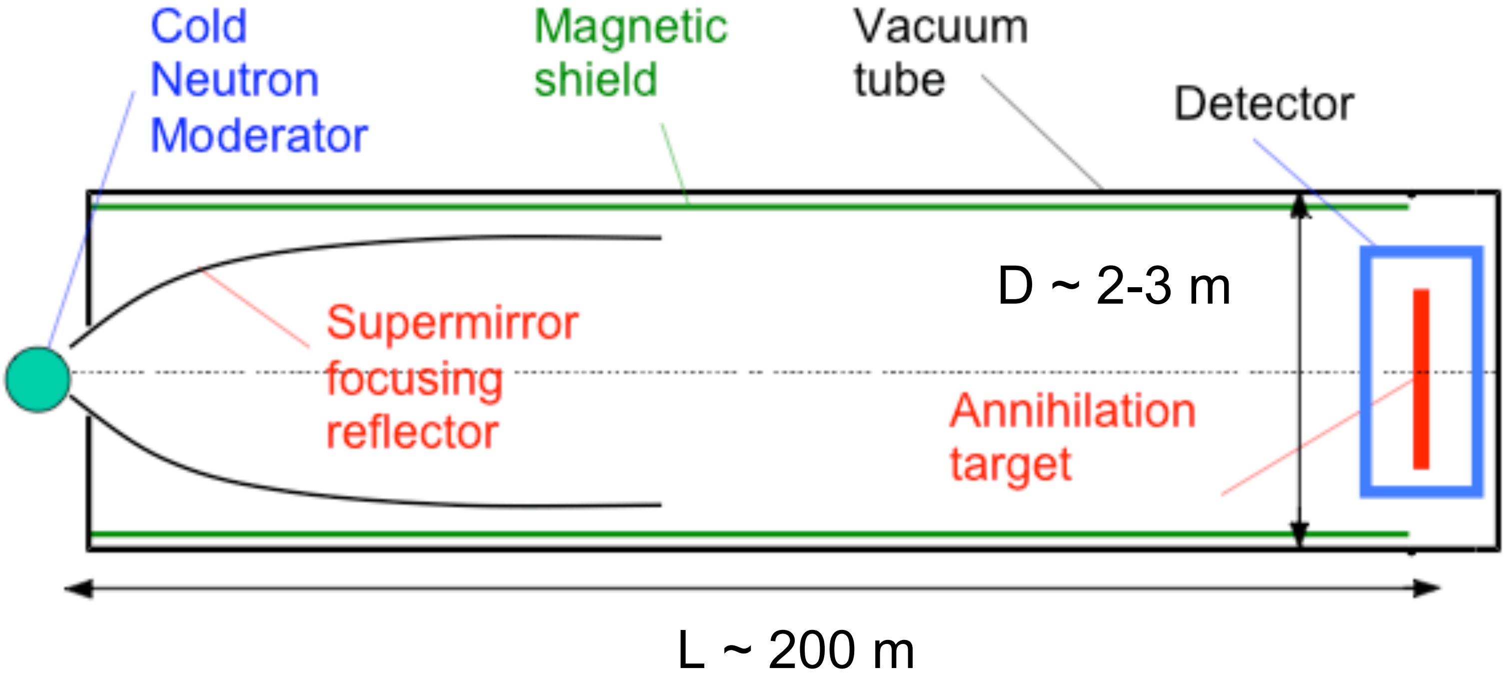
- longer “quasifree” flight time (POSSIBLE)

- longer experiment operation time YES (ILL only ran 1 year)

Better Free Neutron Experiment (Horizontal beam shown: vertical possible)

need slow neutrons from high flux source, access of neutron focusing reflector to cold source, free flight path of ~200m

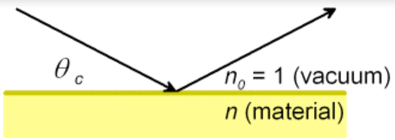
Improvement on ILL experiment by factor of ~1000 in transition probability is possible with horizontal experiment at Project X with existing n optics technology, sources, and moderators. Vertical experiment also possible



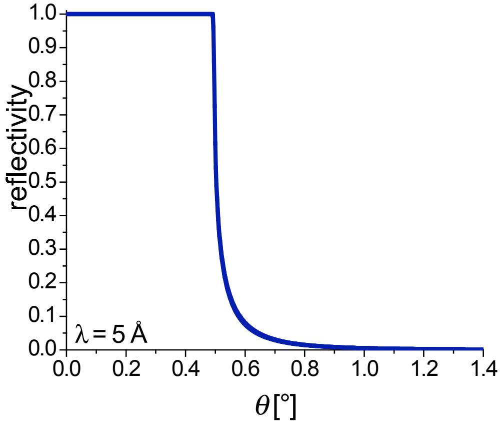
concept of neutron supermirrors: Swiss Neutronics

neutron reflection at grazing incidence (< ≈2°)

@ smooth surfaces

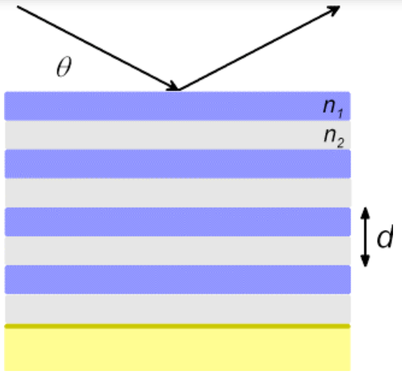


- refractive index $n < 1$
- total external reflection e.g. Ni $\theta_c = 0.1$ °/Å

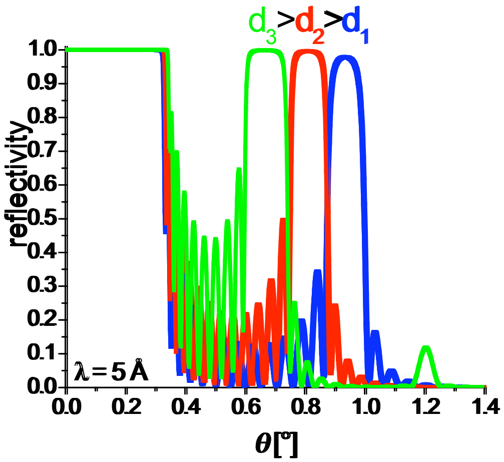


m=1

@ multilayer

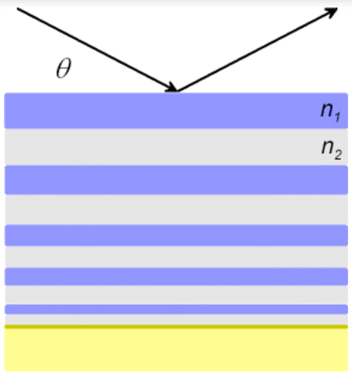


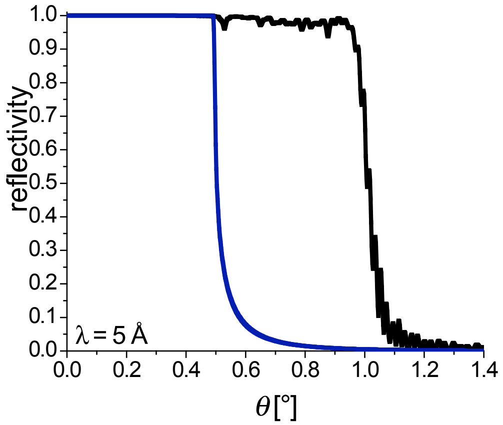
$$\lambda = 2d\sin\theta$$



$\theta_{critical} \rightarrow m\theta_{critical}$

@ supermirror

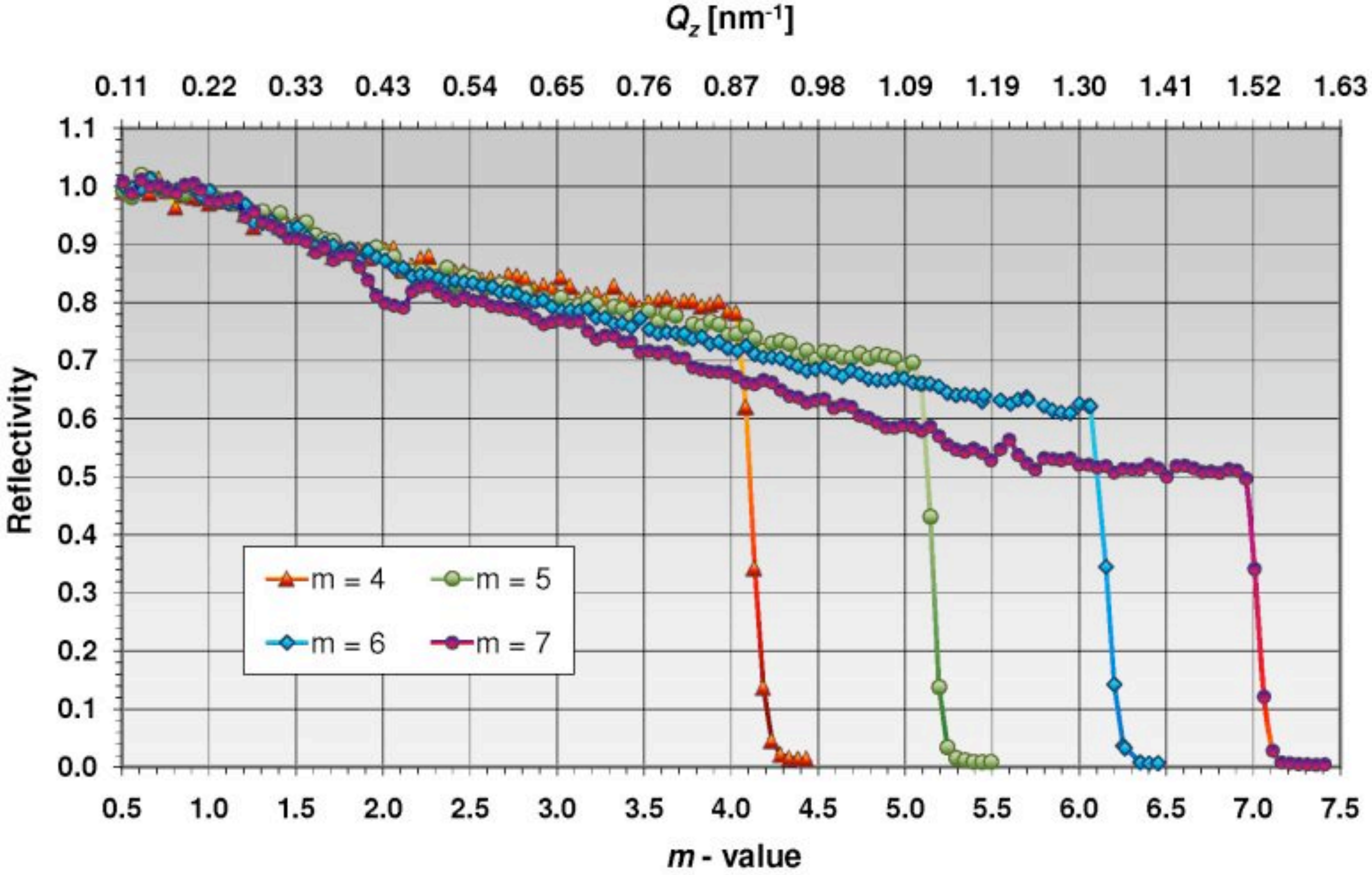




m=2

"Supermirrors": $\theta_{\text{critical}} \rightarrow m\theta_{\text{critical}}$

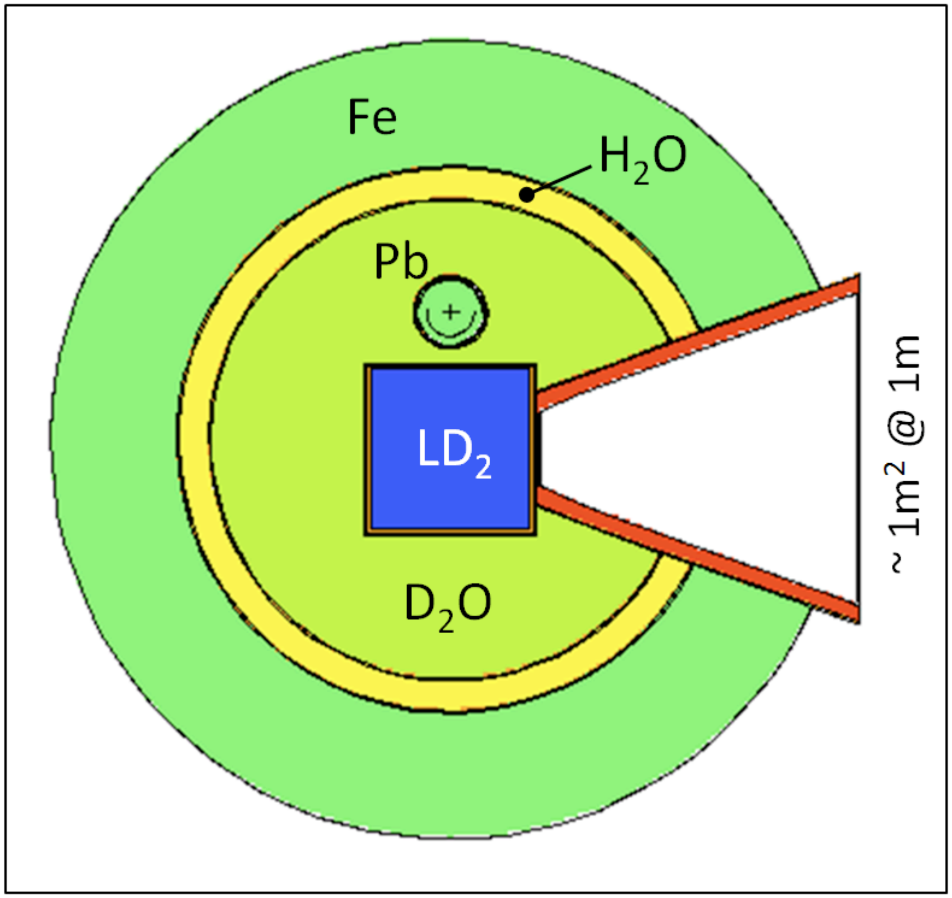
Commercial Supermirror Neutron Mirrors are Available With m up to 7! Phase space acceptance for straight guide $\propto m^2$, more with focusing reflector



ILL experiment used m~1 optics

From P. Boeni, Swiss Neutronics

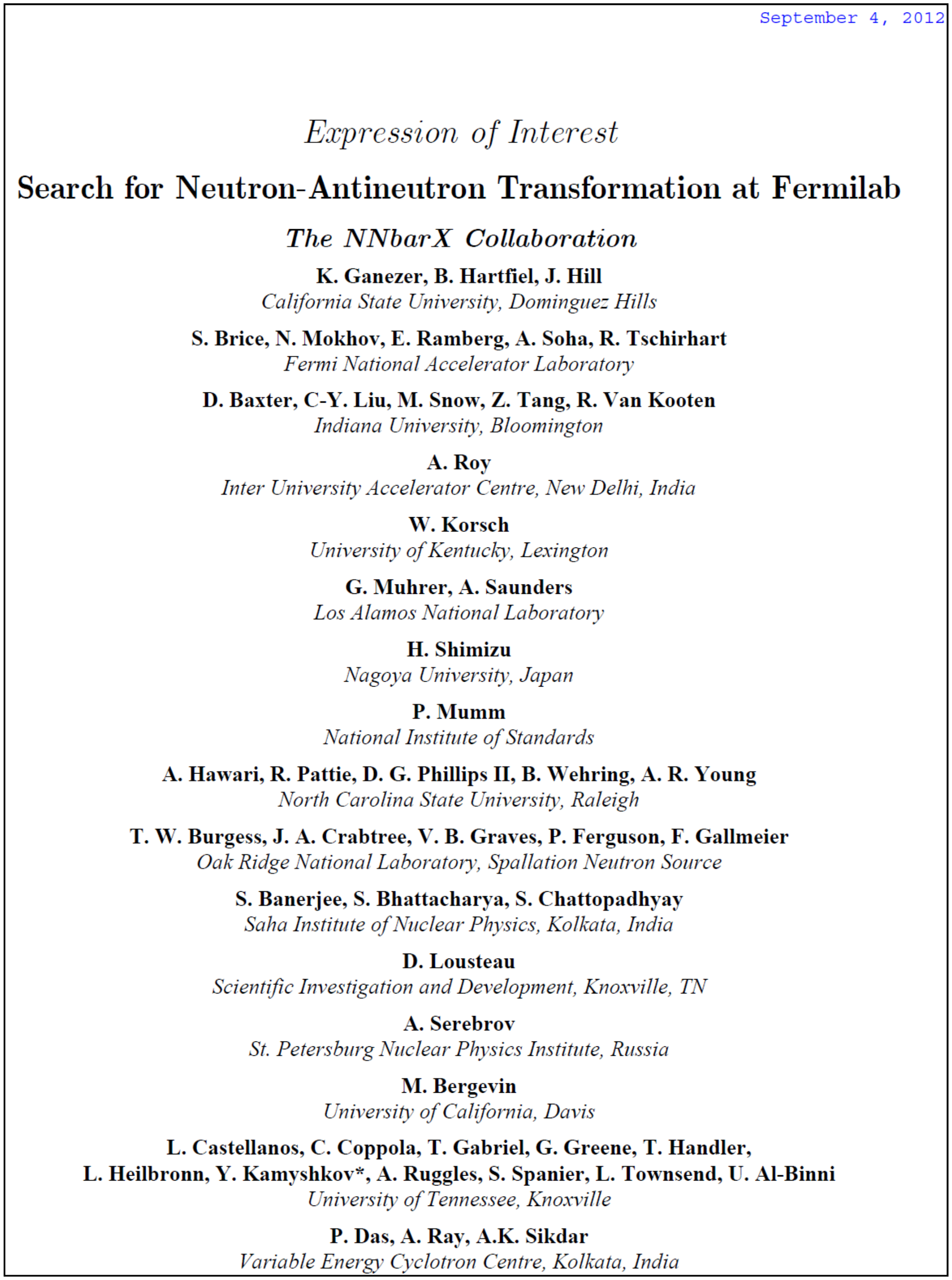
Spallation Target/Moderator/Reflector for Project X nnbar experiment



Baseline based on PSI-type spallation target (1MW CW operation, measured neutron brightness)

Open geometry is not compatible with slow n sources used in neutron scattering facilities

->"green-field" advantage of Project X for this experiment over other 1MW sources



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Expression of Interest

Search for Neutron-Antineutron Transformation at Fermilab

The NNbarX Collaboration

K. Ganezer, B. Hartfiel, J. Hill
California State University, Dominguez Hills

S. Brice, N. Mokhov, E. Ramberg, A. Soha, R. Tschirhart
Fermi National Accelerator Laboratory

D. Baxter, C-Y. Liu, M. Snow, Z. Tang, R. Van Kooten
Indiana University, Bloomington

A. Roy
Inter University Accelerator Centre, New Delhi, India

W. Korsch
University of Kentucky, Lexington

G. Muhrer, A. Saunders
Los Alamos National Laboratory

H. Shimizu
Nagoya University, Japan

P. Mumm
National Institute of Standards

A. Hawari, R. Pattie, D. G. Phillips II, B. Wehring, A. R. Young
North Carolina State University, Raleigh

T. W. Burgess, J. A. Crabtree, V. B. Graves, P. Ferguson, F. Gallmeier
Oak Ridge National Laboratory, Spallation Neutron Source

S. Banerjee, S. Bhattacharya, S. Chattopadhyay
Saha Institute of Nuclear Physics, Kolkata, India

D. Lousteau
Scientific Investigation and Development, Knoxville, TN

A. Serebrov
St. Petersburg Nuclear Physics Institute, Russia

M. Bergevin
University of California, Davis

L. Castellanos, C. Coppola, T. Gabriel, G. Greene, T. Handler,
L. Heilbronn, Y. Kamyshkov*, A. Ruggles, S. Spanier, L. Townsend, U. Al-Binni
University of Tennessee, Knoxville

P. Das, A. Ray, A.K. Sikdar
Variable Energy Cyclotron Centre, Kolkata, India

Approved by Fermilab PAC

New and international participants are welcome!

NNbar Summary

New physics beyond the SM can be discovered by NNbar search

Improvement in free neutron oscillation probability of a factor of ~1,000 is possible

If discovered:

- n→nbar observation would violate B-L by 2 units, establish a new force of nature, illuminate beyond SM physics, and may help to understand matter-antimatter asymmetry of universe

If NOT discovered:

- will set a new limit on the stability of “normal” matter via antimatter transformation channel. Will constrain some scenarios for B-L violation and “post-sphaeleron” baryogenesis

Summary

New physics beyond the Standard Model can be discovered by NNbar search

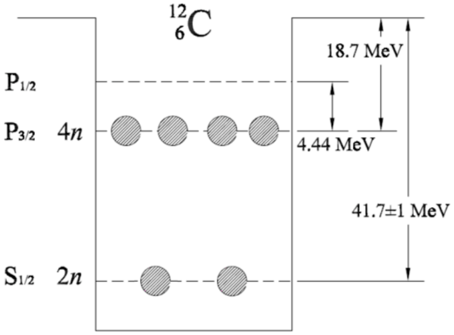
Experiments with free neutrons possess very low backgrounds (sharp vertex localization): ILL experiment observed no background. Interpretation of result is independent of nuclear models. Any positive observation can be turned off experimentally with the application of a small magnetic field.

Sensitivity of free neutron experiment for NNbar transition rate can be improved by factor of ~1000 using existing technology [Combination of improvements in neutron optics technology, longer observation time/larger-scale experiment, and source design optimization at green-field facility]. Further improvements in a free neutron experiment can come from neutron optics technology/moderator/reflector development (see Kamyshkov, Gabriel, Young talks)

US high-energy intensity frontier complex could in principle provide the type of dedicated source of slow neutrons needed for a greatly improved free NNbar experiment.

Suppression of n→nbar in intranuclear transitions

Neutrons inside nuclei are "free" for the time: $\Delta t \sim \dfrac{\hbar}{E_{binding}} \sim \dfrac{\hbar}{30MeV} \sim 4.5 \times 10^{-22} s$



each oscillating with "free" probability $= \left(\dfrac{\Delta t}{\tau_{n\bar{n}}}\right)^2$

and "experiencing free condition" $N = \dfrac{1}{\Delta t}$ times per second.

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

Intranuclear transition (exponential) lifetime: $\boxed{\tau_{\mathrm{A}} = \dfrac{\tau_{n\bar{n}}^2}{\Delta t} = R \leftrightarrow \tau_{n\bar{n}}^2}$

where $\mathrm{R} \sim \dfrac{1}{\Delta \mathrm{t}} \sim 4.5 \leftrightarrow 10^{22} s^{-1}$ is "nuclear suppression factor"

Actual nuclear theory suppression calculations for $^{16}O, ^{2}D, ^{56}Fe, ^{40}Ar$ by C. Dover et al; W.Alberico et al; B.Kopeliovich and J. Hufner, and most recently by Friedman and Gal (2008) corrected this rough estimate within a factor of 2