# Neutron-Antineutron Oscillations With Cold Neutron Beams

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LBL   B-L Workshop

Phenomenology
Cold neutron beams: previous experiment (ILL)
How can the limits be improved?

Thanks for slides: Yuri Kamyshkov, Peter Boeni,…

Related sessions on Saturday:
session 12: experiments with neutrons
session 13: mirror matter search with neutrons

# Neutron-Antineutron Oscillations: Formalism

$\alpha \neq 0$ allows oscillations

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

$H = \begin{pmatrix} E_n & \alpha \\ \alpha & E_{\bar{n}} \end{pmatrix}$ 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 :**

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

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

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

$\langle V_{mag} \rangle = \mu B$, ~60 neV/Tesla

B~1nT-> $V_{mag} \sim 10^{-16}$ eV

For any realistic B field, $\mu B \gg \alpha$

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

# How to Search for N-Nbar Oscillations

Figure of merit for probability: $NT^2$

N=total # of free neutrons observed

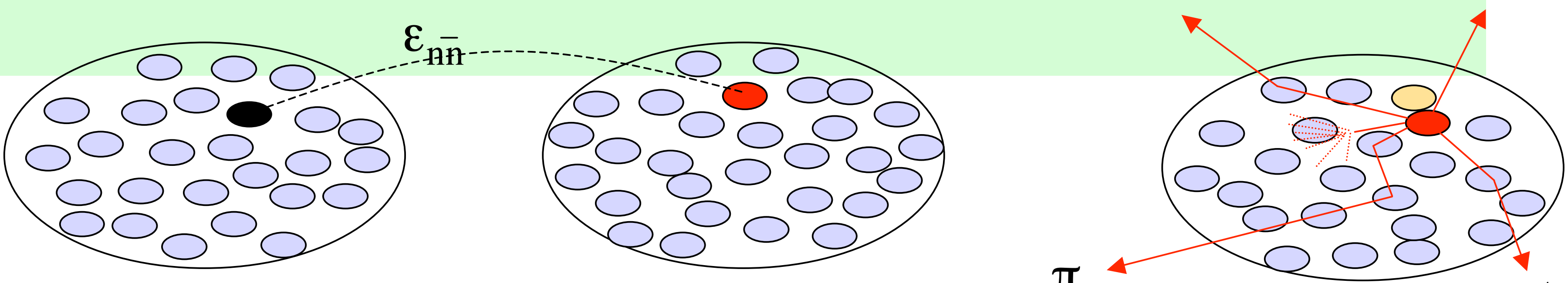
T= observation time per neutron while in "quasifree" condition

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

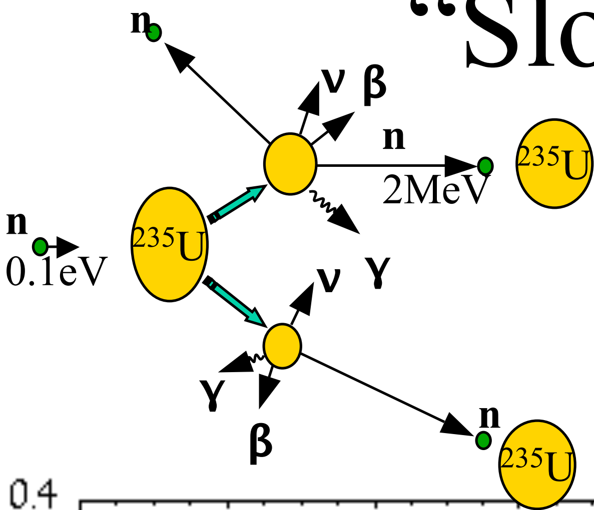
(2) Cold and Ultracold neutrons



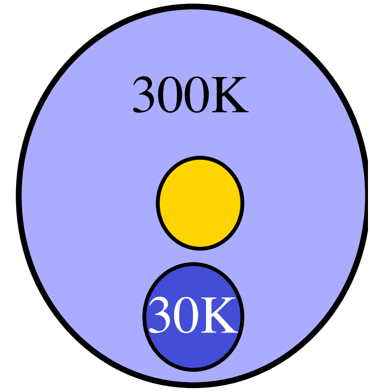

Nucleus $A \rightarrow A^* + \bar{n}$

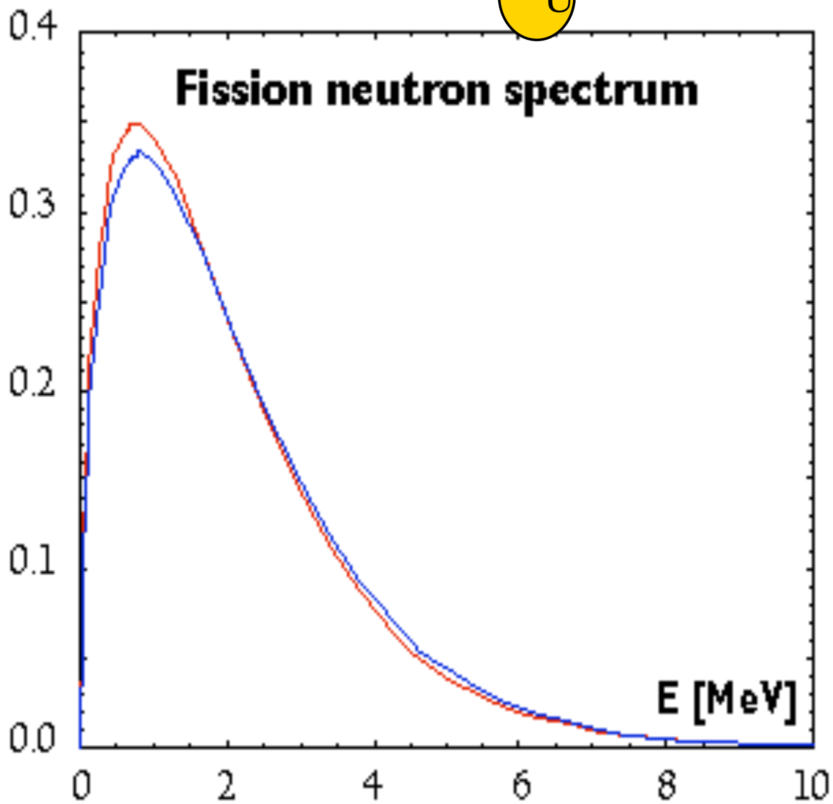
$\bar{n}N \rightarrow$ pions

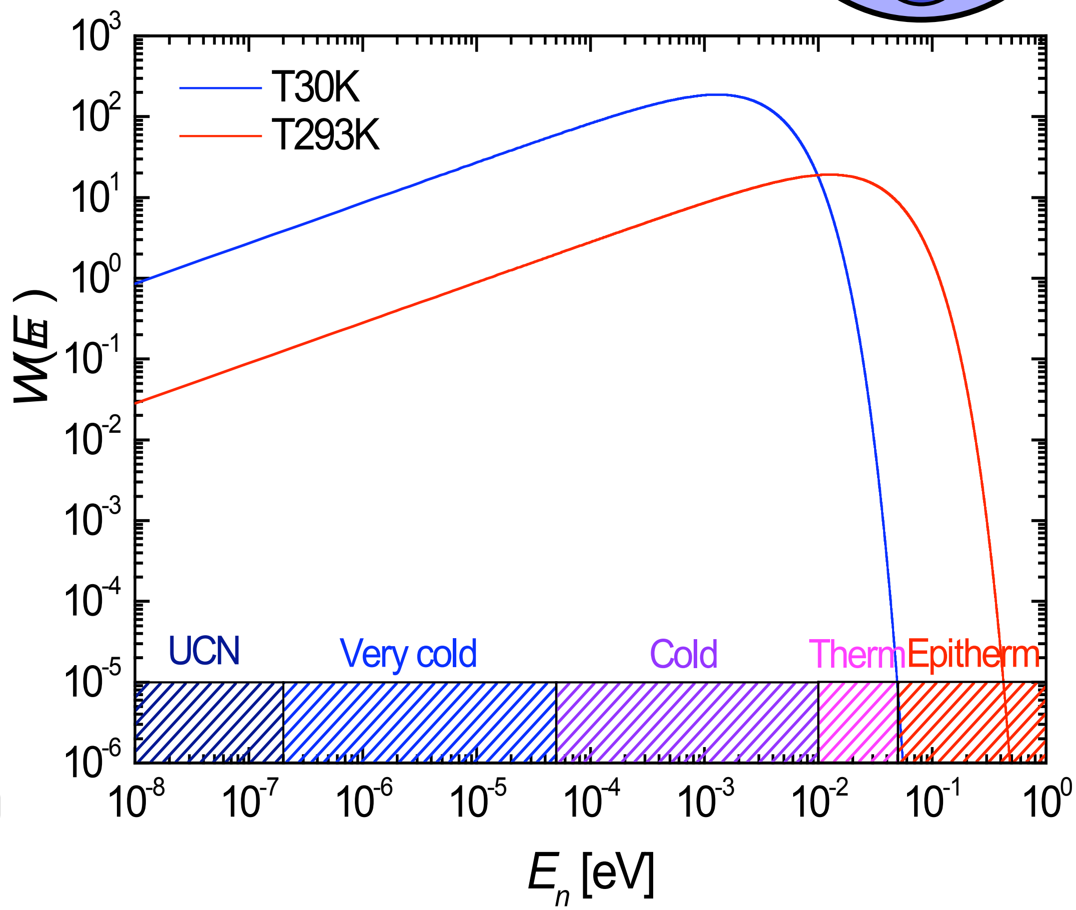
# “Slow” Neutrons: MeV to neV




Nuclear reactor



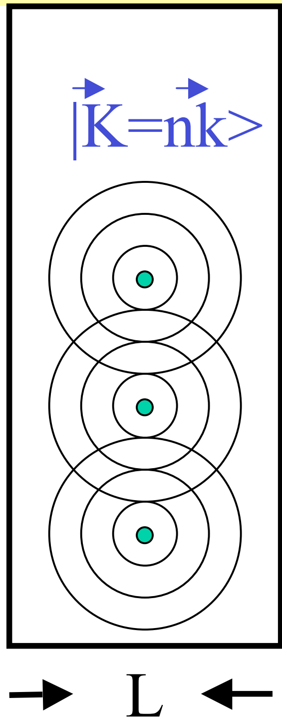



# Neutron Optics

$|\vec{k}\rangle$

$|\vec{K}=n\vec{k}\rangle$




$e^{i\phi}|\vec{k}\rangle$

Phase shift $\phi=(n-1)kL$

Index of refraction

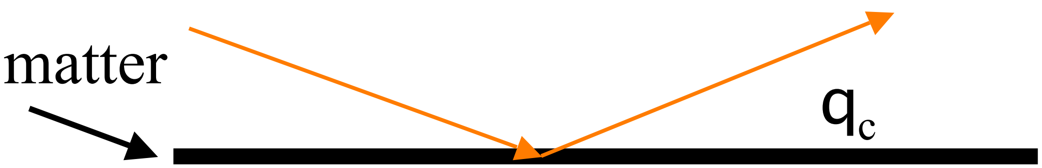
$n=|K|/|k|=\sqrt{[(E_k-\langle V\rangle)/E_k]}$

$kR>>1$

s-wave

$f_{scatt}=b$

matter




$q_c=\lambda\sqrt{[\rho b/\pi]}$ critical angle

$\langle V_{strong}\rangle=2\pi h^2\rho b_s/m$, ~+/- 100 neV

$\langle V_{mag}\rangle=\mu B$, ~+/- 60 neV/Tesla

$\langle V_{grav}\rangle=mgz$~100 neV/m

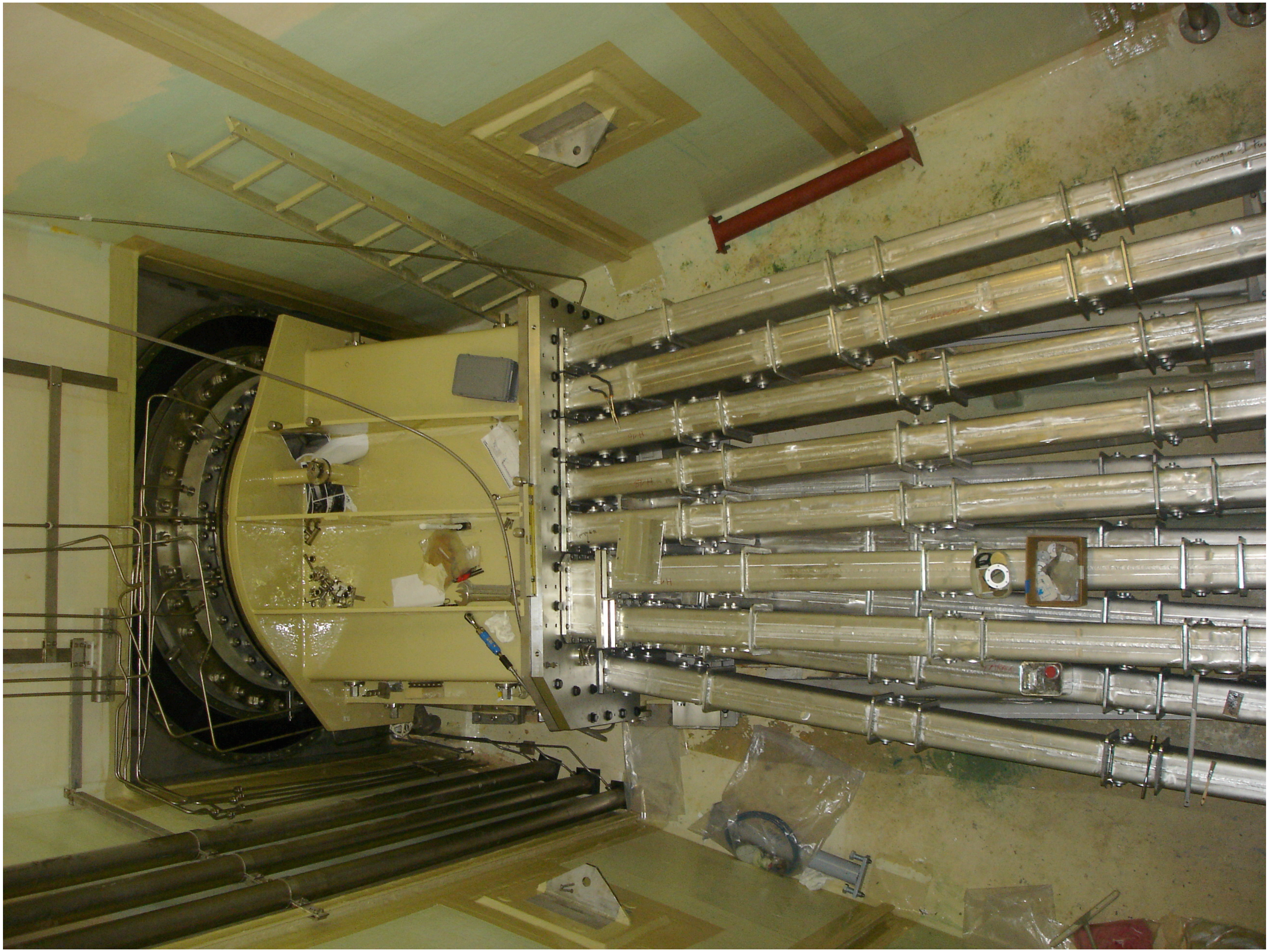
$\langle V_{weak}\rangle=[2\pi h^2\rho b_w/m]\vec{s}\cdot\vec{k}/|k|$~$10^{-7}\langle V_{strong}\rangle$

For $E_k-\langle V\rangle$ negative,

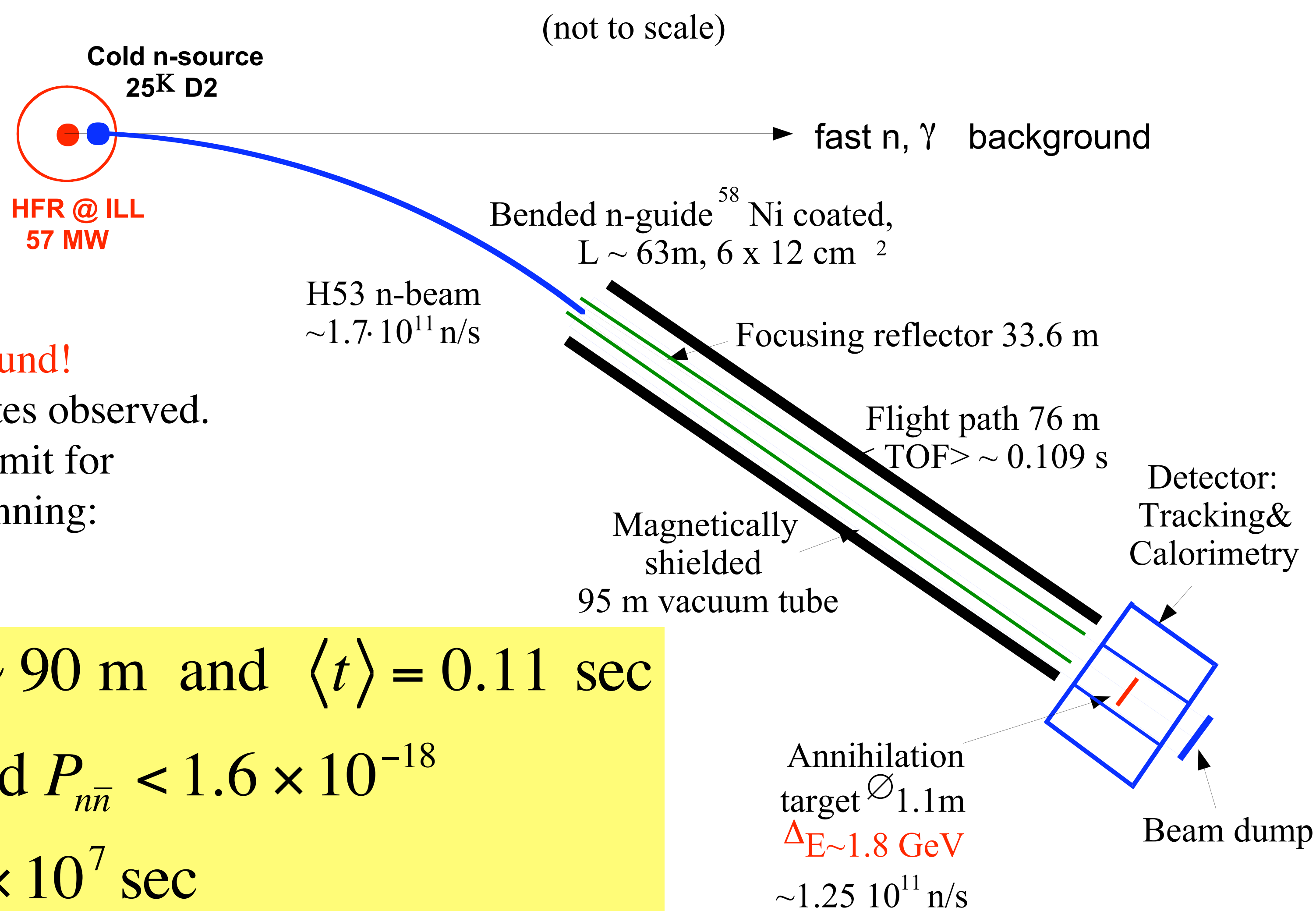
neutron reflects

from the optical potential

# Neutron guides at ILL (top view)



# Best free neutron search at ILL/Grenoble reactor by Heidelberg-ILL-Padova-Pavia Collaboration




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

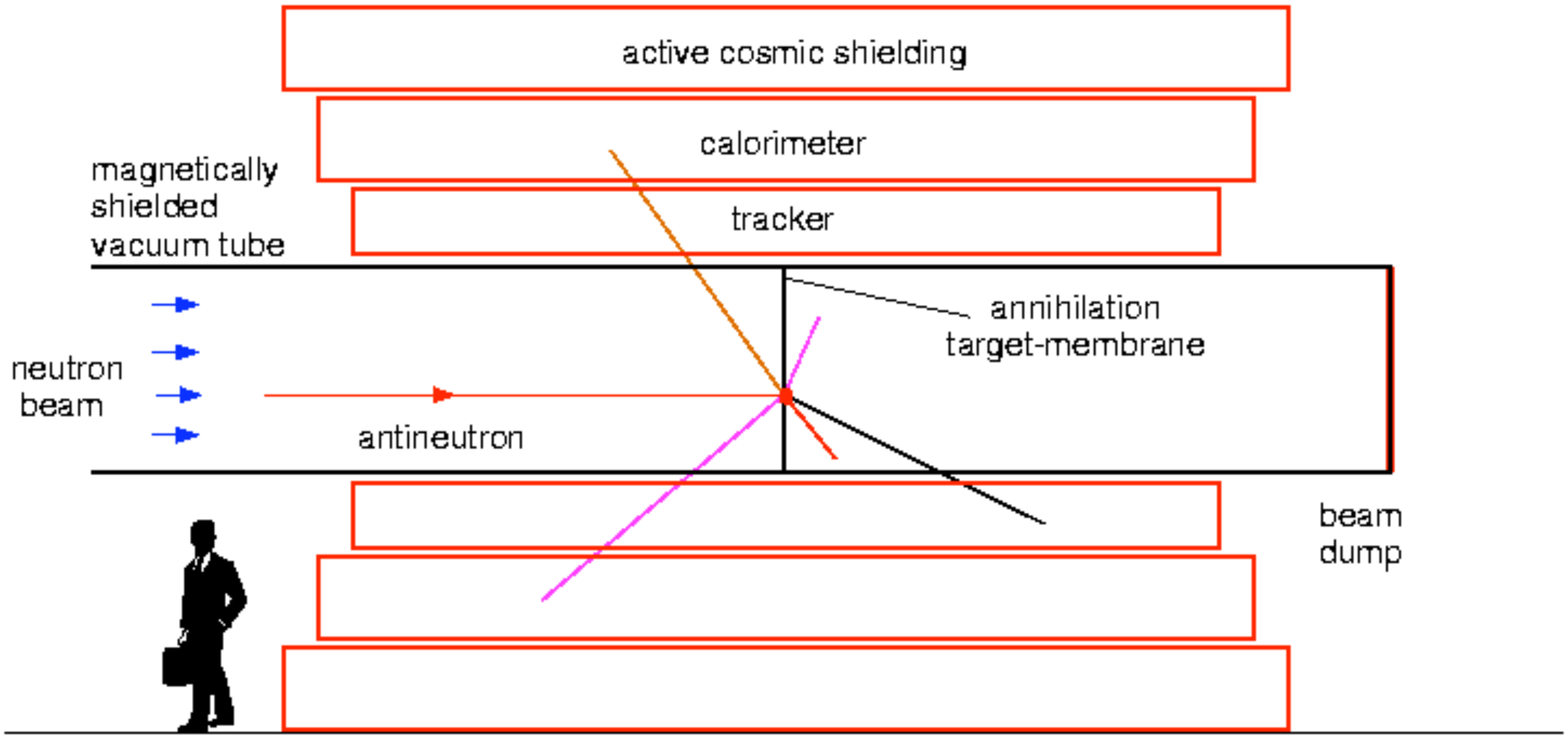
$$\text{with L} \sim 90\text{ m and } \langle t\rangle = 0.11 \text{ sec}$$

$$\text{measured } P_{n\bar{n}} < 1.6\times10^{-18}$$

$$\tau > 8.6\times10^{7}\text{ sec}$$

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

# The conceptual scheme of antineutron detector




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

Annihilation target: ~100μ thick Carbon film

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

# How to Improve on ILL Experiment with Cold Neutrons?

-difficult to shift neutron spectrum (research problem in neutron moderator materials/cryogenic engineering for future “very cold neutron” (VCN) sources) NO

Must:

-increase phase space acceptance of neutrons from source YES

-increase observation time YES

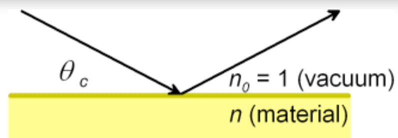
While, at the same time,

-maintaining quasifree condition

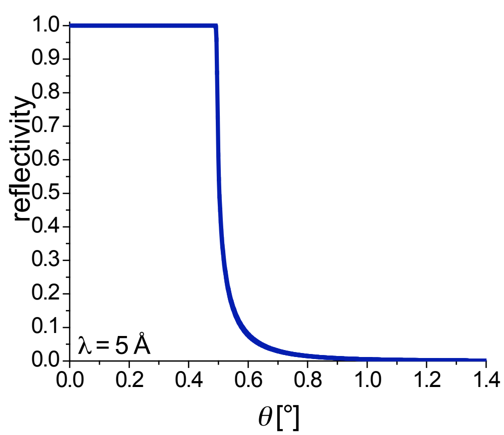
# concept of neutron supermirrors: Swiss Neutronics

## neutron reflection at grazing incidence (< ≈2°)

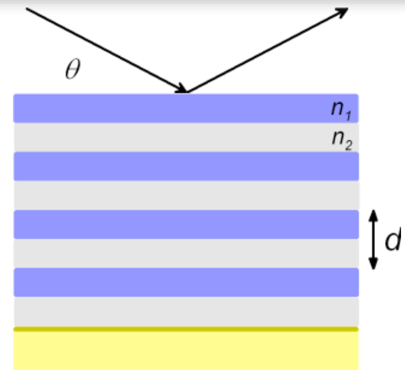
### @ smooth surfaces



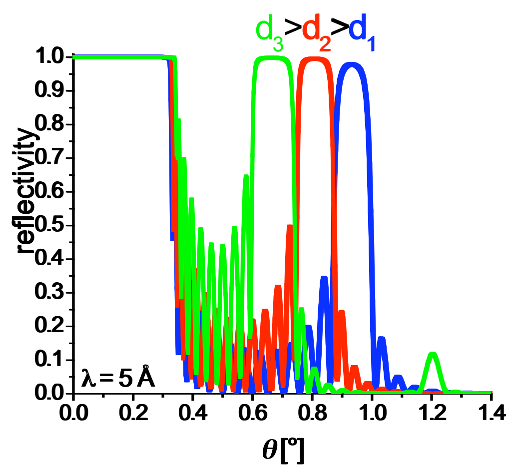

- refractive index $n$ < 1
- total external reflection
  e.g. Ni $q_c$ = 0.1 °/Å



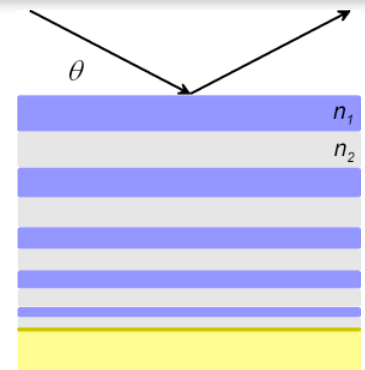

### @ multilayer

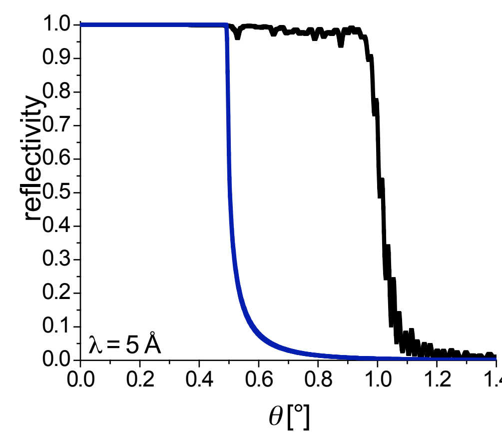



$$\lambda = 2d\sin\theta$$



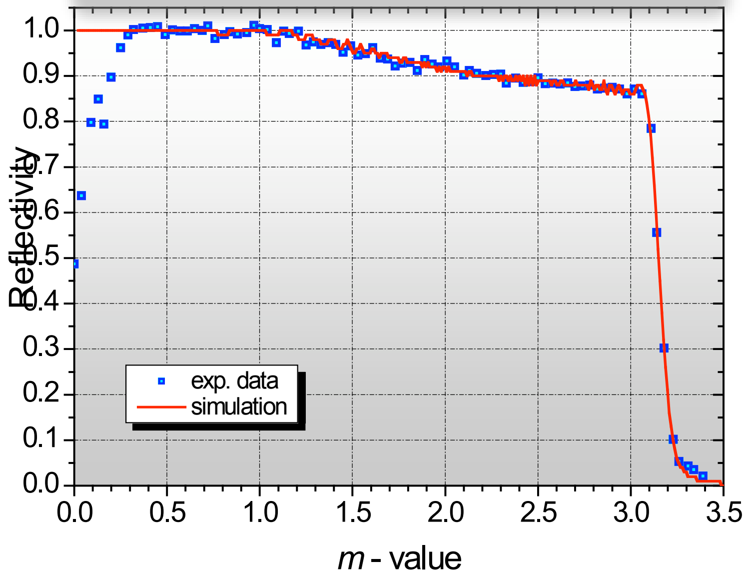

### @ supermirror



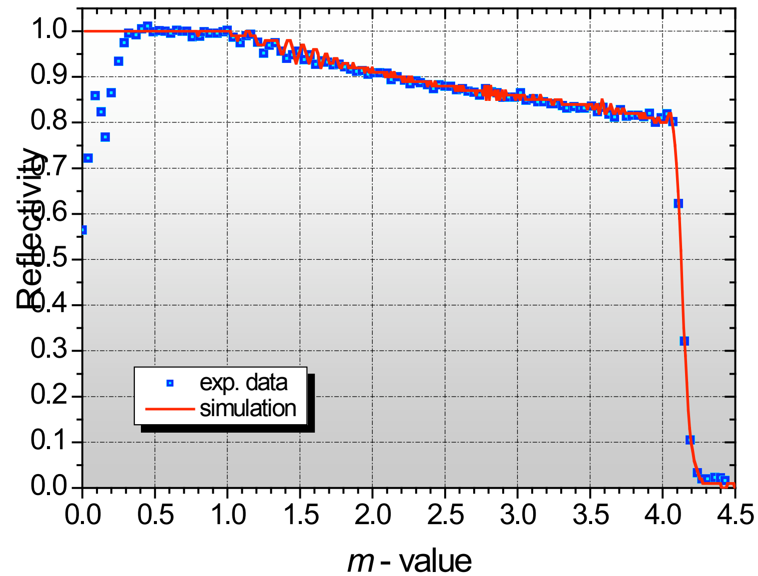



# *Ni/Ti supermirrors – high 'm' : Swiss Neutronics*

**m = 3**




**m = 4**




**reflectivity simulation:** *SimulReflec V1.60*, F. Ott, http://www-llb.cea.fr/prism/programs/simulreflec/simulreflec.html, 2005

$\theta_c = m\theta_{58Ni}$ defines m

Research and development on higher m in progress
(see Shimizu talk)

# Supermirror Neutron Optics: Elliptical Focusing Guides

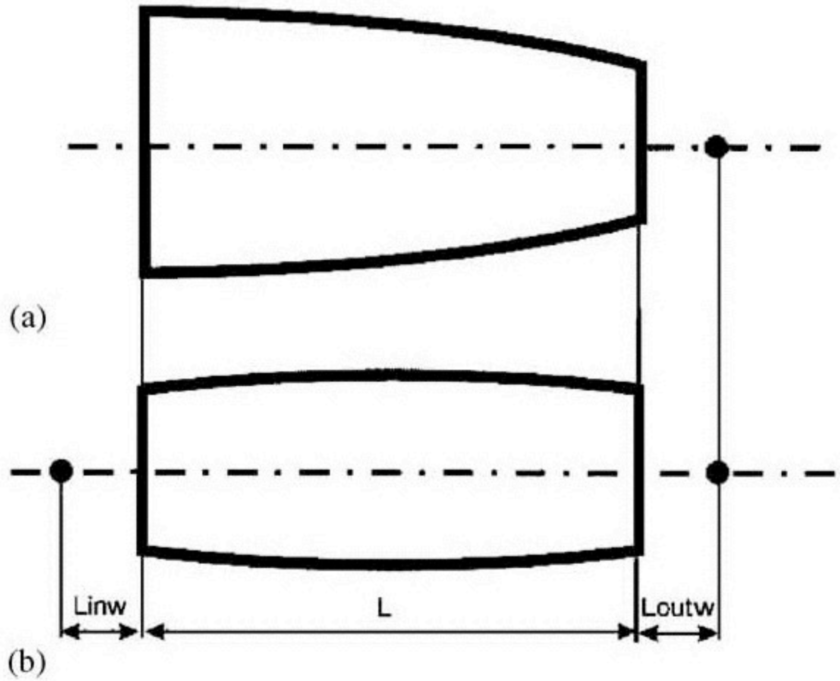



Fig. 1. Parameters for the (a) parabolic and (b) elliptic focusing guide in the $x$-plane.

Muhlbauer et. al., Physica B 385, 1247 (2006).

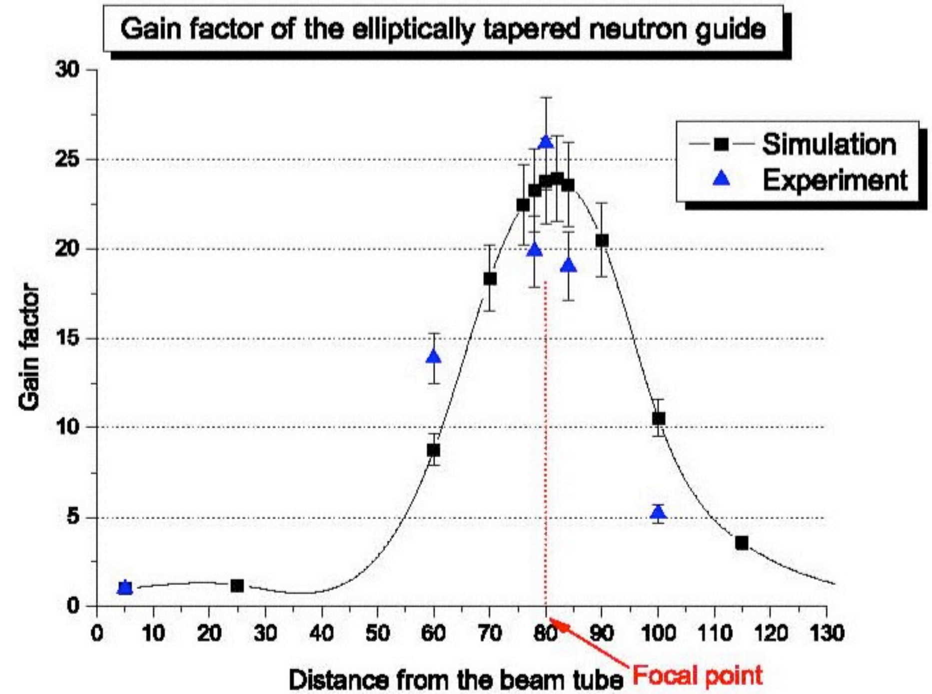
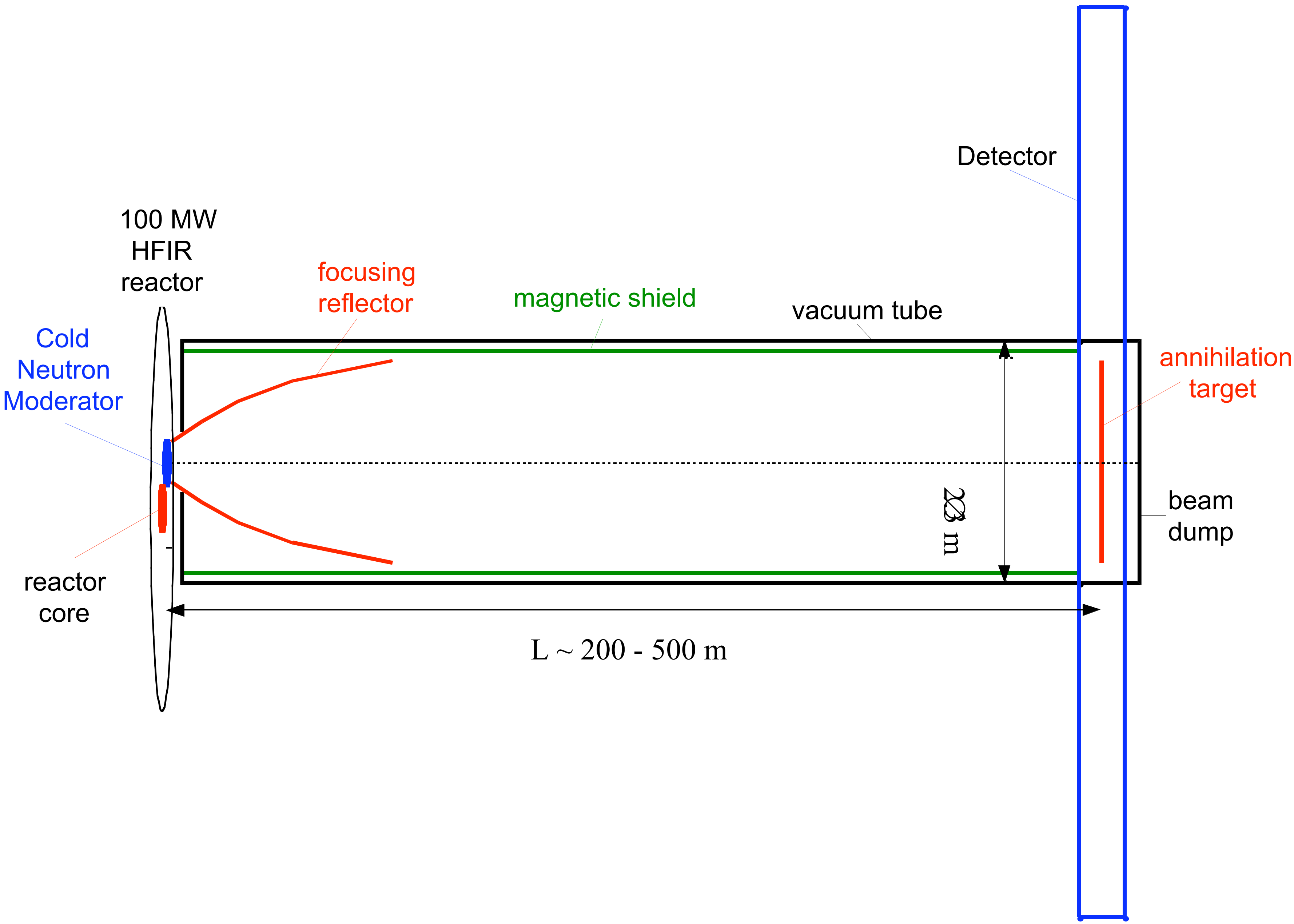



Fig. 3. Neutron intensity as measured and calculated versus distance from the exit of the guide. Clearly seen is the point of maximum intensity near $F_2 = 80\,\mathrm{mm}$.

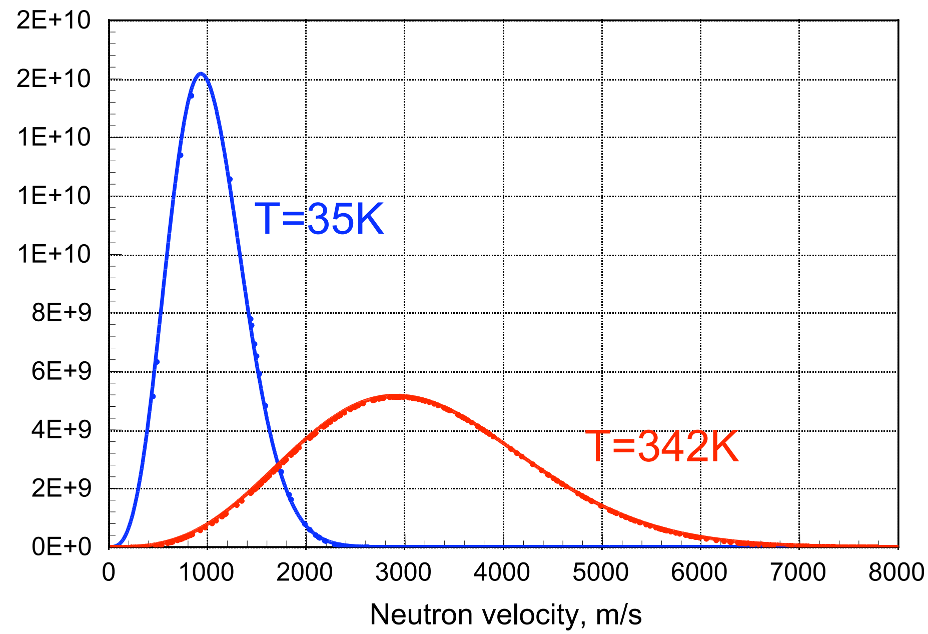
Under development for neutron scattering spectrometers (WISH @ISIS)

Can be used to increase fraction of neutrons delivered from cold source (cold source at one focus, nbar detector at other focus)

# Concept for Horizontal N-Nbar search



# Practical limit on horizontal cold neutron experiment from gravity




For 1-km initially horizontal flight path the vertical displacement due to gravity acceleration is ~ 5m for $V_X$=1000 m/s and t=1 sec; vertical velocity component is $V_Y$=10 m/s

→ Gravitational defocusing effect on cold neutrons for horizontal beam layout

→ Vertical beam layout preserves all the cold spectrum and allows max path length

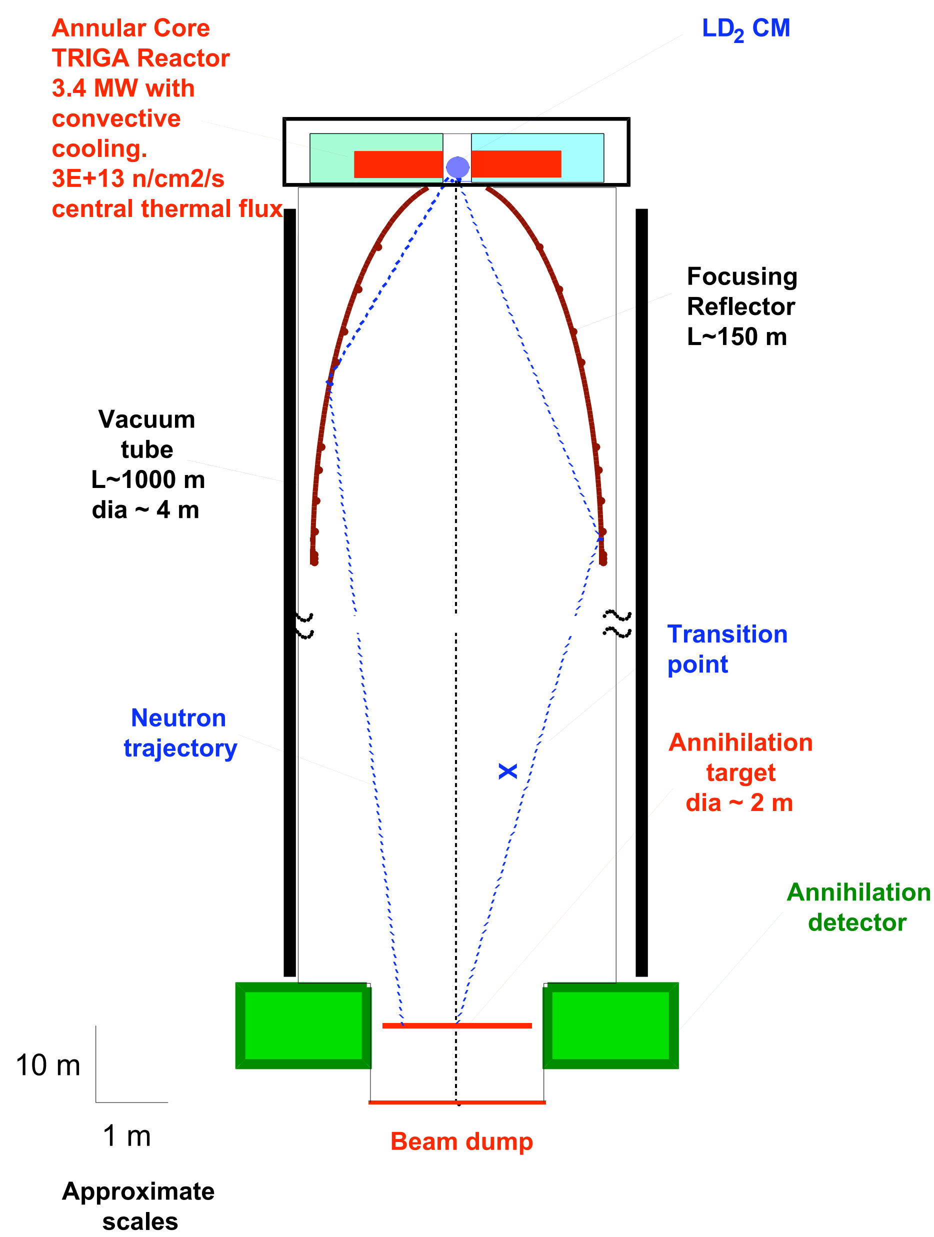
For vertical layout with focusing :

$$\text{Sensitivity} \propto \frac{L^2}{T^{3/2}}$$

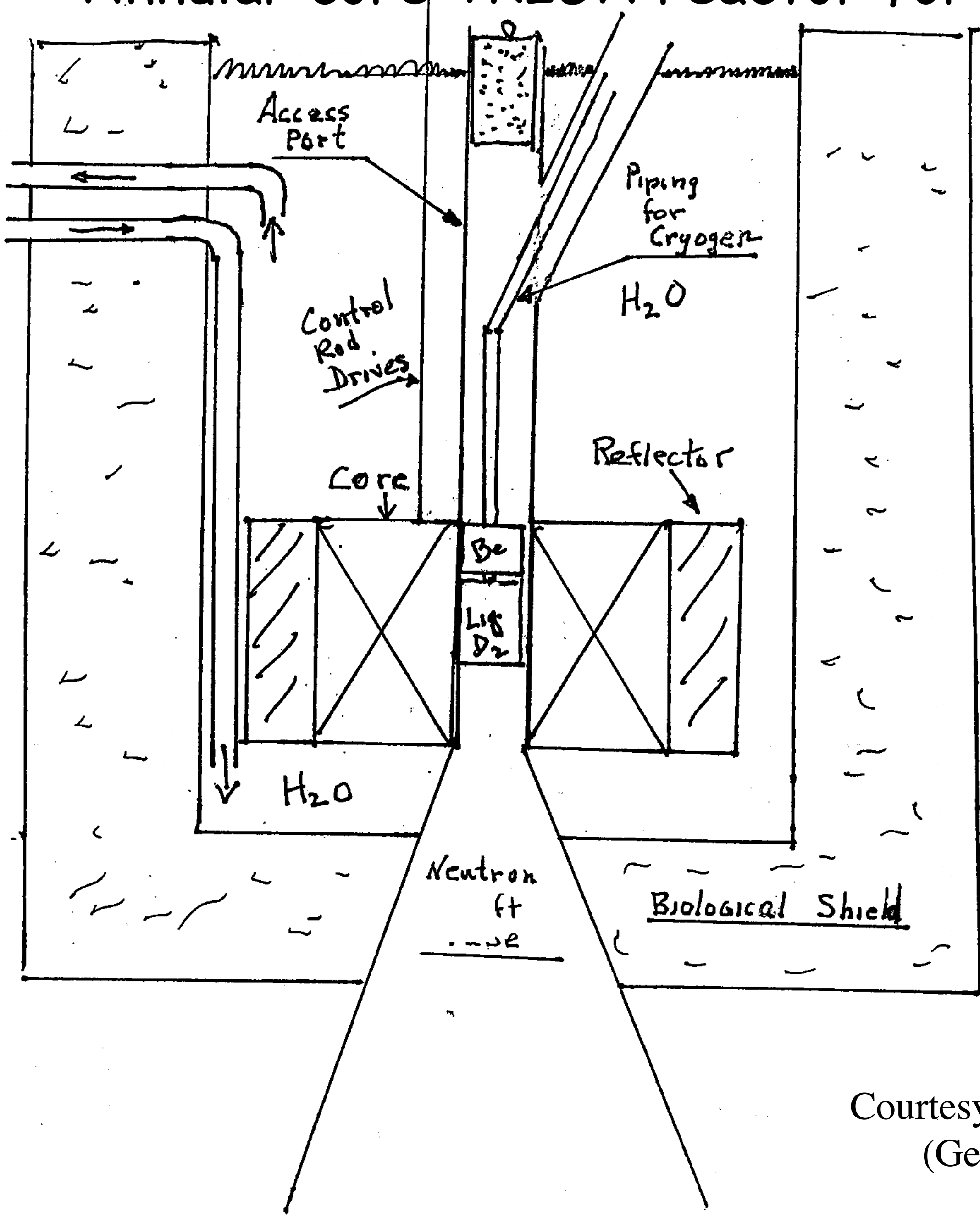
# Scheme of N-Nbar search experiment at DUSEL

- Dedicated small-power TRIGA research reactor with cold neutron moderator → $v_n \sim 1000$ m/s
- Vertical shaft ~1000 m deep with diameter ~ 6 m at DUSEL
- Large vacuum tube, focusing reflector, Earth magnetic field compensation system
- Detector (similar to ILL N-Nbar detector) at the bottom of shaft

Letter of intent to DUSEL submitted



# Annular core TRIGA reactor for N-Nbar search experiment




Annular core TRIGA reactor 3.4 MW with convective cooling, vertical channel, and large cold moderator. Unperturbed thermal flux in the vertical channel 3E+13 n/cm$^2$/s

Cold moderator has been placed in vertical arrangement before:

PNPI WWR-M reactor : 18 MW reactor,
Vertical cold source in core
20K Liquid hydrogen moderator

Courtesy of W. Whittemore
(General Atomics)

# Vertical Cold Neutron Source (PNPI)

Delivered to new Australian research reactor, 18 MW power

Cold source for TRIGA could be similar

# Quasifree Condition $\mu B t << \hbar$ : B Shielding

ILL achieved |B|<10 nT over 1m diameter, 80 m beam, 1% reduction in oscillation efficiency (Bitter et al, NIM A309, 521 (1991).

Need |B|<1 nT next version for same efficiency (flight time 0.1 s->~1s)

Also need vacuum to keep $V_{opt} t << \hbar$

P<$10^{-5}$ Pa is good enough.

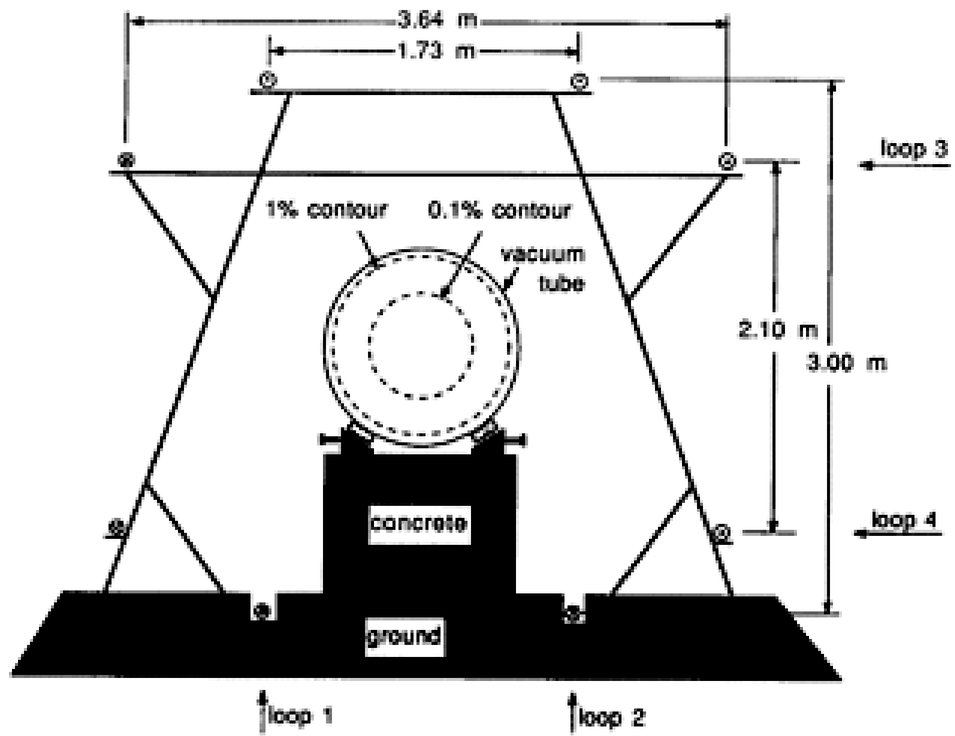



Fig. 10. The transverse field compensation system. Loops 1 and 2 are under 49 A current and compensate the horizontal field component; loops 3 and 4 are under 120 A current and compensate the vertical field component.

# Quasifree Condition: Verification

Performed by polarized neutrons and use of neutron spin echo spectroscopy (U. Schmidt et al, NIM A320, 569 (1992).

Need polarizers and analyzers with larger phase space acceptance to polarize and analyze beam



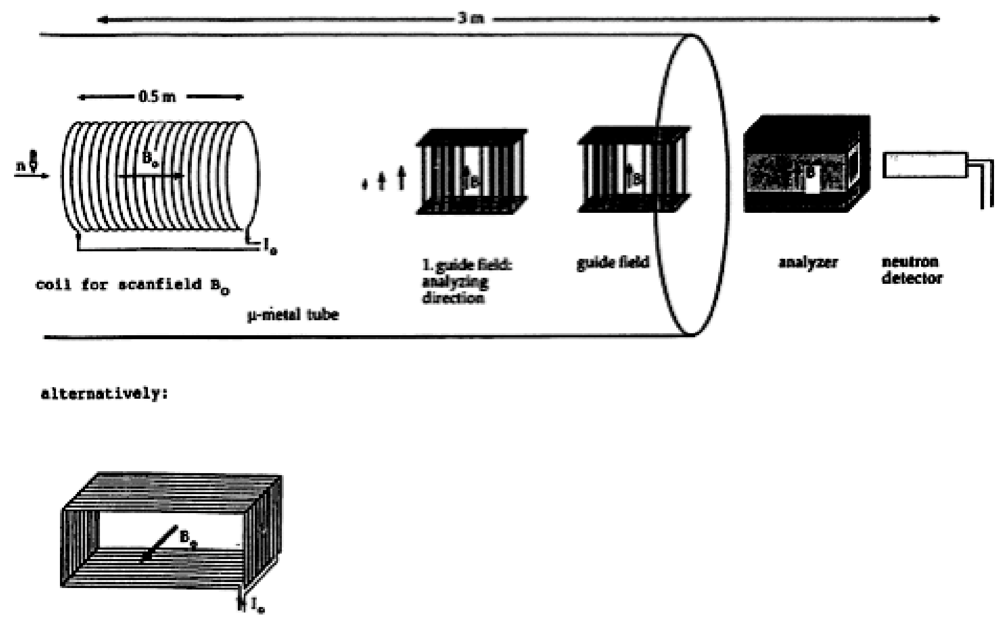



Fig. 3. Polarized neutron analyser equipment at the exit of the zero-field region, at 70 m distance to the polarizers of fig. 2.

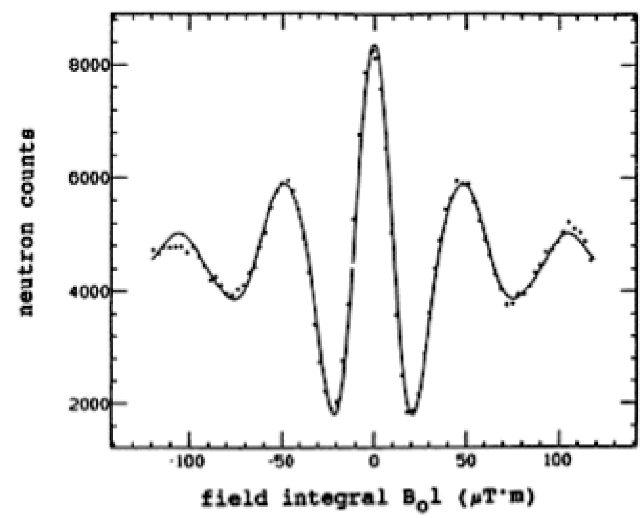
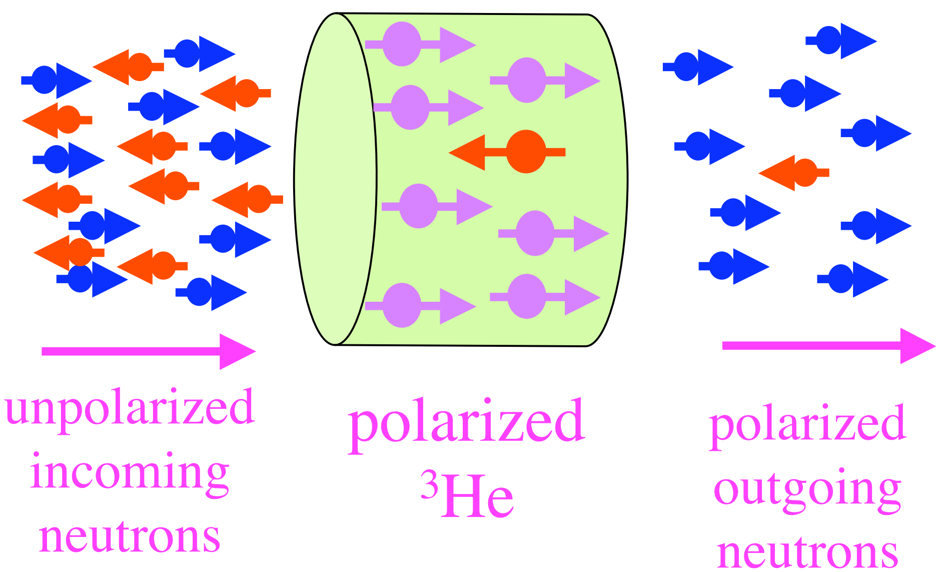
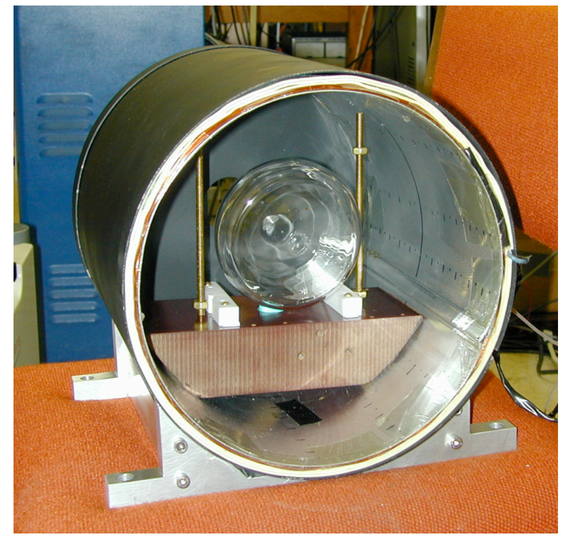



Fig. 4. Neutron-spin echo curve produced with the apparatus of figs. 2 and 3. The zero-offset of this curve measures the residual magnetic field along the magnetically shielded 70 m long neutron beam line to $\langle B_z \rangle = 4$ nT, via a neutron spin precession angle of $\phi = 2°$. The solid line is a fit to the theoretical lineshape.

# POLARIZED $^3$He for Neutron Polarimetry

Need to measure B over nnbar flight path. Use neutrons as magnetometers. Polarize/analyze neutron beam using 3He



*Polarized $^3$He cell (11 cm diameter)*

**Large neutron phase space acceptance**

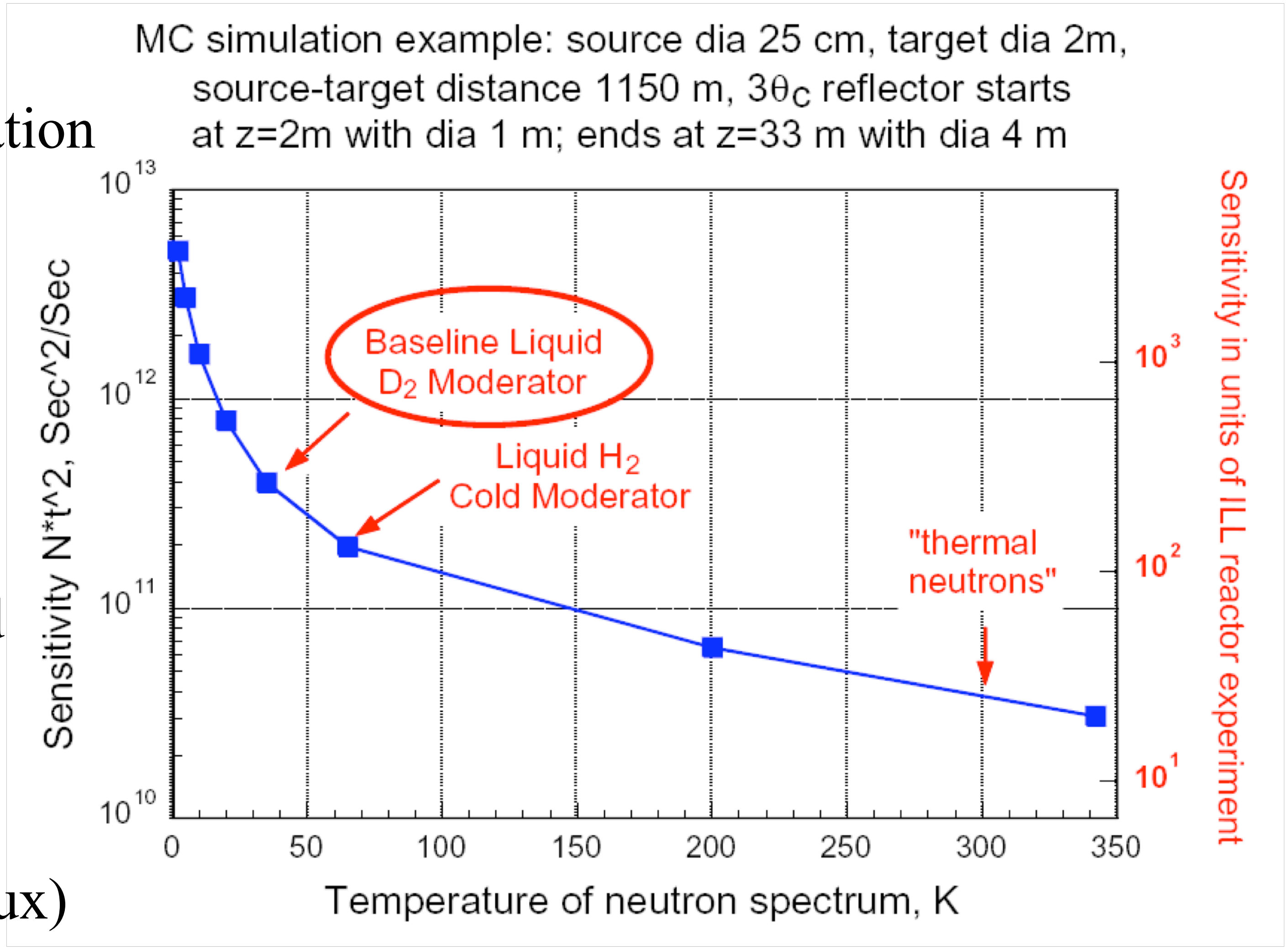
**Polarizer/analyzer pair can measure B using neutron spin rotation**

*NIST, Indiana, Hamilton, Wisconsin* *NSF CAREER→DEFG0203ER46093*

# Sensitivity of vertical experiment

For 3 years operation improvement in limit on transition rate is ~1000

horizontal experiment could be comparable (shorter length compensated by higher neutron flux)



# Conclusions

Sensitivity of cold neutron experiment for n-nbar transition rate can be improved by factor of ~1000. Combination of improvements in neutron optics technology and larger-scale experiment

Clearly serious engineering and other issues remain to be addressed before any vertical experiment can be seriously proposed. Work on these issues is in progress

# Quasifree Condition

ILL experiment achieved |B|<10 nT over 1m diameter, 100 m beam, 1% reduction in oscillation efficiency (Bitter et al, NIM A309, 521 (1991).

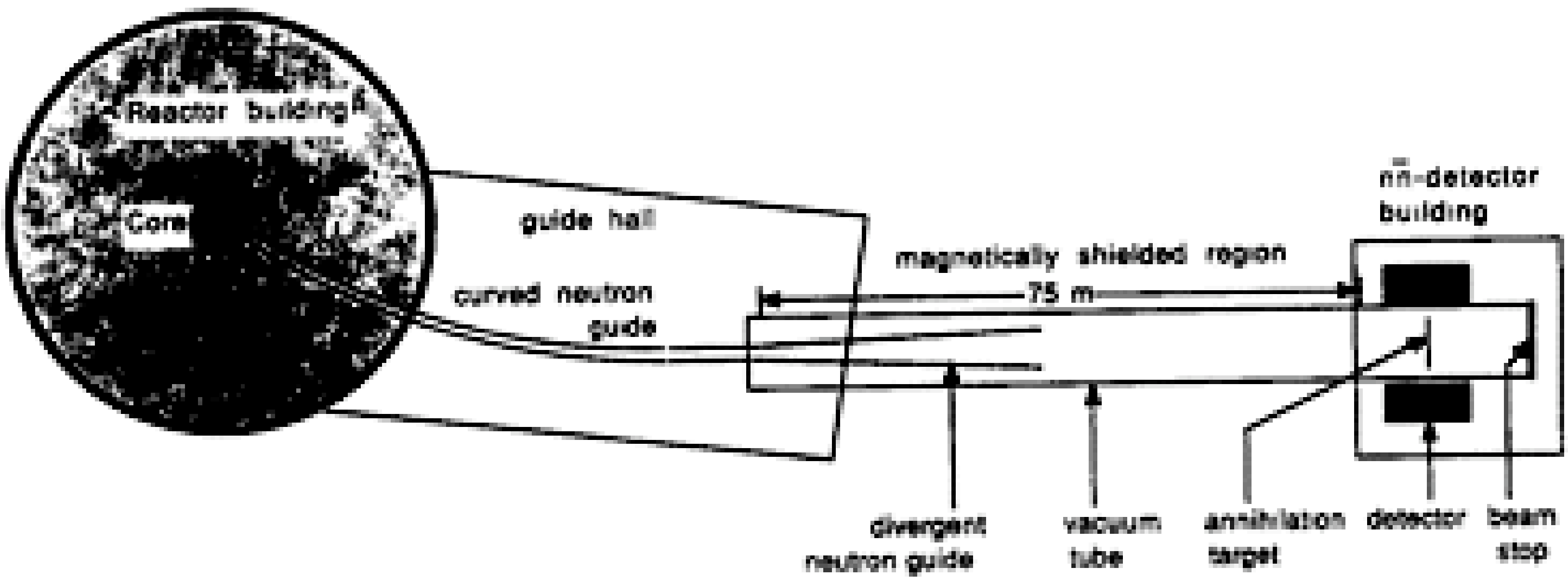



Fig. 1. Schematics of the neutron–antineutron oscillation experimental setup at the Institut Laue–Langevin.

# $n \to \bar{n}$ Search Sensitivity

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

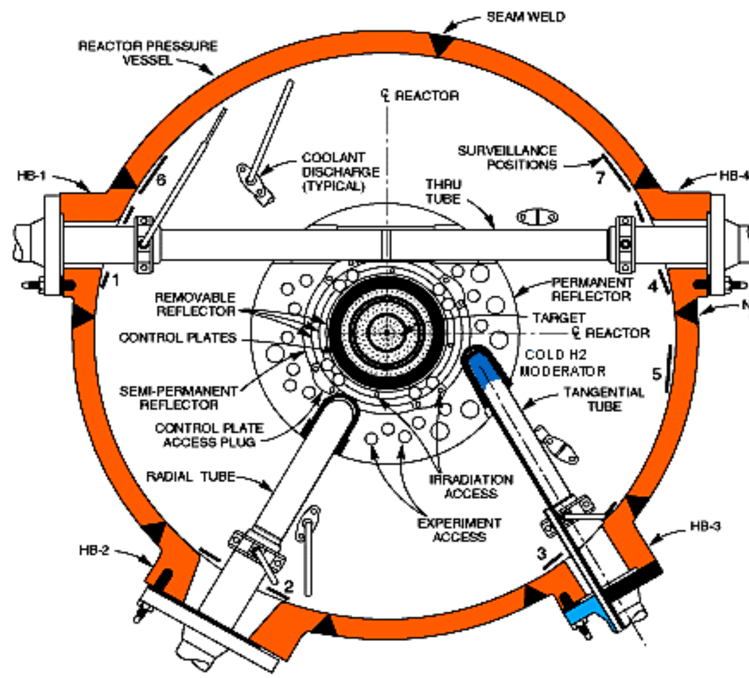
| Method | Present limit | Possible future limit | Possible sensitivity increase factor |
|---|---|---|---|
| Intranuclear (in N-decay expts) | $7.2 \cdot 10^{31}$ yr = 1u Soudan II | $7.5 \cdot 10^{32}$ yr (Super-K) $4.8 \cdot 10^{32}$ yr (SNO) | × 16 u (*) |
| Geo-chemical (ORNL) | none | $4 \cdot 10^{8} \div 1 \cdot 10^{9}$ s (Tc in Sn ore) | × 20÷100 u (*) |
| UCN trap ($6 \times 10^{7}$ ucn/sec) | none | ~ $1 \cdot 10^{9}$ s | × 100 u (**) |
| Cold horizontal beam | $8.6 \cdot 10^{7}$ s = 1u @ILL/Grenoble | > $3 \cdot 10^{9}$ s (e.g. HFIR@ORNL) | × 1,000 u (***) |
| Cold Vertcal beam | none | > $3 \cdot 10^{9}$ s (TRIGA 3.4 MW) | × 1,000 u (***) |

# New Experiment at Existing Research Reactor?

- need cold neutron source at high flux reactor, close access of neutron focusing reflector to cold source, free flight path of >~300m

- No luck so far

HFIR reactor at ORNL




Cutaway view HFIR

# $n \leftrightarrow \bar{n}$ transitions — "too crazy"?

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

$K^0, B^0 \longleftrightarrow$ ( $2^{nd}$ order weak interactions ) $\longleftrightarrow \bar{K}^0, \bar{B}^0$

And neutral fermions can oscillate too -

$\nu_\mu \longleftrightarrow ( \ldots ) \longleftrightarrow \nu_\tau$

So why not -

$n \longleftrightarrow$ ( New physics ) $\longleftrightarrow \bar{n}$ ?

Such systems are interferometers, sensitive to small effects. Neutron is a long-lived neutral particle ($q_n < 10^{-21}e$) with a distinct antiparticle and so can oscillate. No oscillations have been seen yet.

Need interaction beyond the Standard Model that violates Baryon number (B) by 2 units.

# B conservation in SM is Approximate

From SM point of view, both <u>B and L conservation are "accidental"</u> global symmetries: given $SU(3)\otimes SU(2)\otimes U(1)$ gauge theory and matter content, no dimension-4 term in Lagrangian violates B or L. No special reason why SM extensions should conserve B.

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

Nonperturbative EW gauge field fluctuations present in SM, VIOLATE <u>both B and L, but conserve B-L.</u> Rate can be faster than expansion rate at the electroweak phase transition in early universe.

B asymmetry of the universe exists