Neutron-Antineutron Oscillations: Can Current Experimental Limits Be Improved?

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what is it?
why is it interesting? (B-L violation)
Phenomenology
Limits from underground detectors
Possibility of UCN
Cold neutron beams

Thanks for slides: Yuri Kamyshkov, Tony Mann, Albert Young, Yasuhiro Masuda, Peter Boeni

$n \leftrightarrow \bar{n}$ transitions — “too crazy”?

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

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

And neutral fermions can oscillate too -

ν_μ ⟷ (. . .) ⟷ ν_τ

So why not -

n ⟷ (New physics) ⟷ $\bar{n}$?

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. Why should such an interaction exist?

Is B the Source of a Field Like Q?

Conservation of electric charge is closely connected with U(1) gauge symmetry/masslessness of photon/ 1/r form of EM potential.

$$V_{EM} = Q / r$$

If same idea worked for B, we expect conservation of "baryonic" charge to be associated with new long-range force coupled to B. So where is the new long-range force coupled to B?

$$V_B = B / r$$

Experimental tests of equivalence principle for gravity (Eot-Wash, etc.) use masses with different B/M ratios, see no effects. This give strong constraint on any such new long-range force coupled to B.

B conservation in SM is Approximate

From SM point of view, both B and L conservation are "accidental" global symmetries: given SU(3)⊗SU(2)⊗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.

Operator of dimension D+4 is nonrenormalizable term which must be divided by mass scale M^D. Need suppression by large mass scale so that perturbative corrections are small

No evidence that B is locally conserved like Q: where is the macroscopic B force? (EotWash etc. do not see it in EP tests).

Nonperturbative EW gauge field fluctuations called sphalerons, present in SM, VIOLATE both B and L, but conserve B-L. Rate is completely negligible in our vacuum, but should be faster than expansion rate at the electroweak phase transition in early universe.

Two Important Classes of B Violation

In violation of baryon number the conservation of angular momentum requires that spin of nucleon should be transferred to another fermion (lepton or baryon):

That leads to the selection rule:
$\Delta B = \pm \Delta L$ or $|\Delta(B-L)| = 0, 2$

- In Standard Model

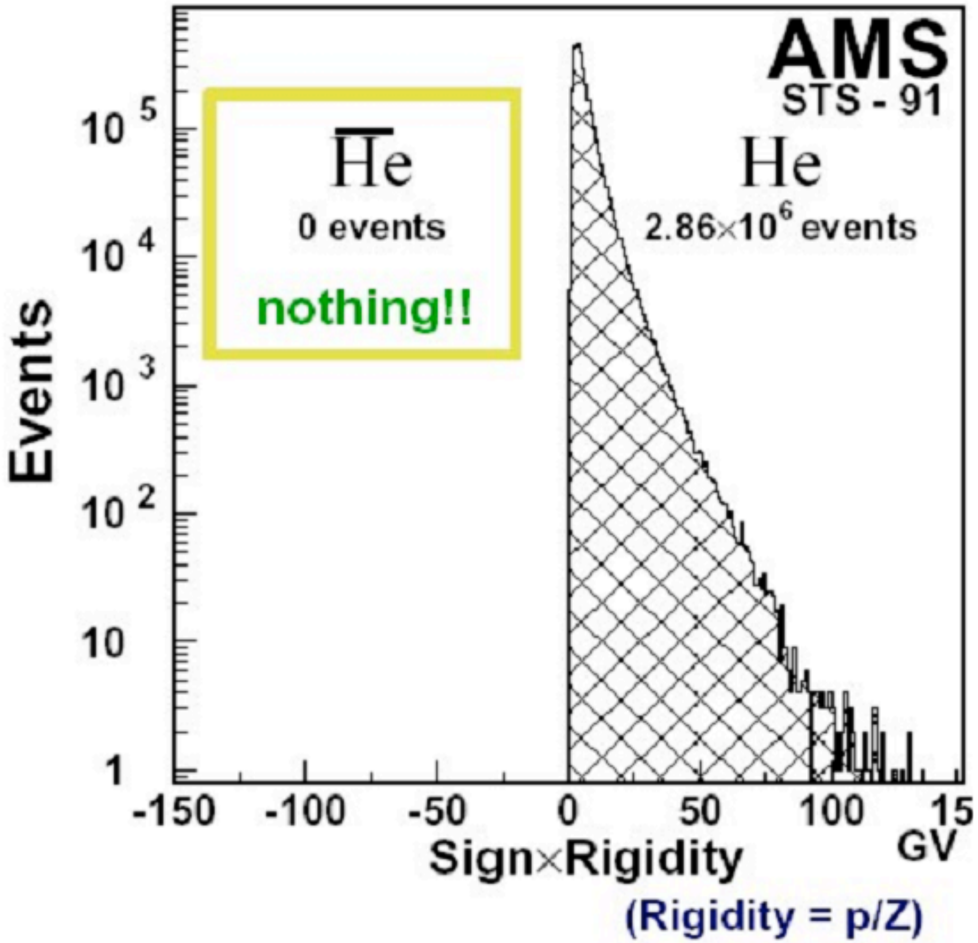
  $\Delta(B-L) = 0$ or $\Delta B = + \Delta L$ (e.g. nucleon $\rightarrow$ antilepton)

- Second possibility of $|\Delta(B-L)| = 2$ also allows transitions with

  $\Delta B = - \Delta L$ (nucleon $\rightarrow$ lepton), $|\Delta B| = 2$, and $|\Delta L| = 2$

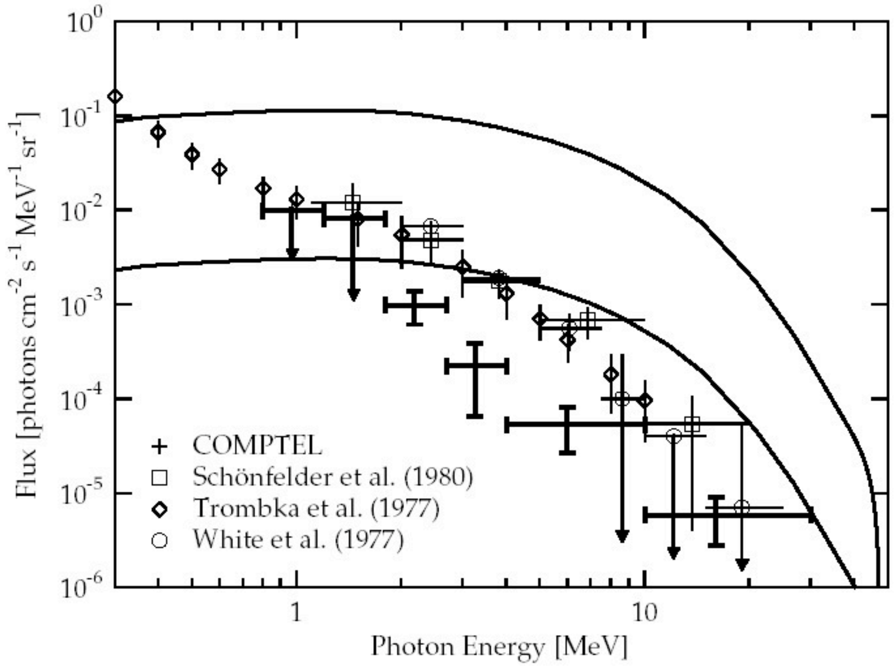
Conservation or violation of $(B-L)$ determines the mechanism of baryon instability.

Universe is B Asymmetric out to ~10 Mpc



"Search for antihelium in cosmic rays"
Phys. Lett. B461 (1999) 387.

Diffuse γ-ray flux
expected from annihilation



Cohen, De Rujula, Glashow;
astro-ph/9707087

In the lab we make equal amounts of matter and antimatter
But the universe has B asymmetry: $\eta = (N_B - N_{antiB}) / N_\gamma \sim 10^{-10}$ Why?

One Possibility: B conservation+ "Initial Condition" $\eta(t{\sim}0)=10^{-10}$

But now we believe in inflationary period in early universe to solve horizon, flatness, etc. problems in cosmology. Inflation asserts that the "size" of the universe increased exponentially at constant energy density:

$$R(t) \propto \exp(3Ht)$$

Inflation needs ~70 Hubble times with universe at ~constant E density -> for conserved B charge, B(t=0)~exp(200)*B(t=after inflation).

But if B(t=after inflation)~10^{-10}, B(t=after inflation-7H^{-1})~1, so rapidly-changing E density of matter with B soon dominates.

->B conservation + $\eta=10^{-10}$ destroys inflation. [A. D. Dolgov, Physics Reports 222,309 (1992).]

Sakharov conditions for Baryon Asymmetry in Big Bang starting from B(t=after inflation)=0

A.D. Sakharov, JETP Lett. 5, 24-27, 1967

Baryon number violation

- Not allowed in SM in perturbation theory.
- Permitted in nonperturbative tunneling processes in SM at EW phase transition, but these conserve B-L

Departure from thermal equilibrium

- Expansion of Universe
- Phase transitions
- Should not be a problem

T violation

- SM CP/T violation from CKM phase seems to be orders of magnitude too small to explain observed B asymmetry – we seem to need new physics here.

Impact of B-L-conserving SM interaction on B asymmetry

Sphaeleron mechanism in Standard Model lead to violation of lepton and baryon number ('t Hooft, 1976)

- "On anomalous electroweak baryon-number non-conservation in the early universe" (Kuzmin, Rubakov, Shaposhnikov, 1985)

Sphaelerons conserve ($B-L$) but violate ($B+L$). Rate of ($B+L$)-violating processes at T > TeV exceeds the Universe expansion rate. If $B=L\neq 0$ is set at GUT scale due to $B-L$ conserving process, B asymmetry can be wiped out by ($B+L$)-violating process

<u>Thus, for the explanation of universe B asymmetry, B-L-violating mechanisms (leptogenesis, NNbar, some nucleon decay modes…) seem to be required</u>

"Proton decay is not a prediction of baryogenesis" [Yanagida'02]

Does Universe have a (B–L) asymmetry as well?

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

$$(B-L) \neq 0$$

- However, in the Universe most of the leptons exist as (yet undetected) relic neutrino and antineutrino radiation (similar to CMBR) and conservation of (B–L) on the scale of the whole Universe is still an open question

- We will be unable to infer possible universal (B-L) asymmetry until we can detect relic neutrinos

Experimental searches for B Violation: Nucleon Decay and Neutron-Antineutron Oscillations

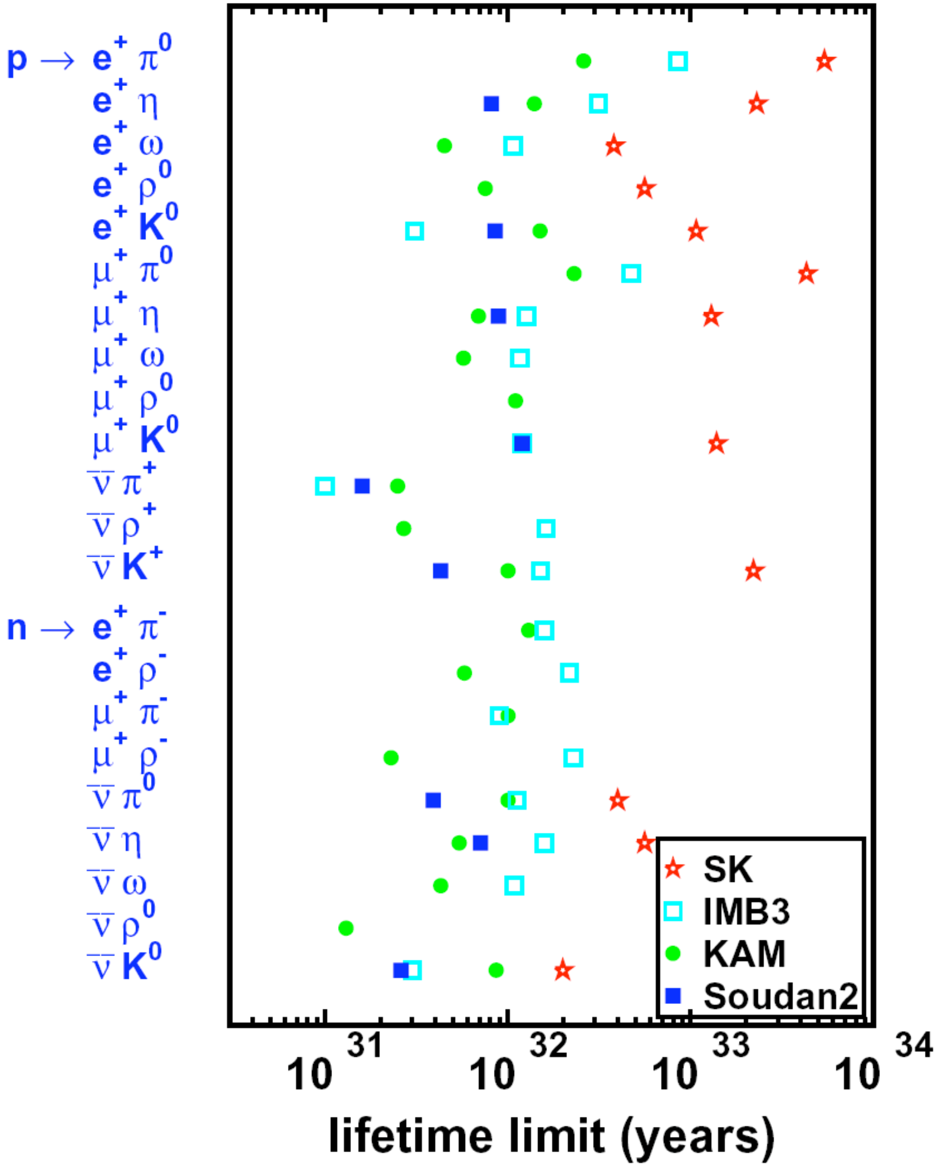
Mode	Nucleon decay	N-Nbar oscillations
Effect on B and L	$\Delta B=1$, $\Delta L=1$, others <u>$\Delta(B\text{-}L)=0,2,\ldots$</u>	$\Delta B=2$, $\Delta L=0$, <u>$\Delta(B\text{-}L)=2$</u>
Effective operator	$L=\frac{g}{M^2}QQQL$	$L=\frac{g}{M^5}QQQQQQ$
Mass scale probed	~GUT	>~EW

Nucleon decay limits: Super-K, Soudan-2, IMB3, Kamiokande, Fréjus

All these modes Δ(B−L)=0

Many (not all) GUTS dead

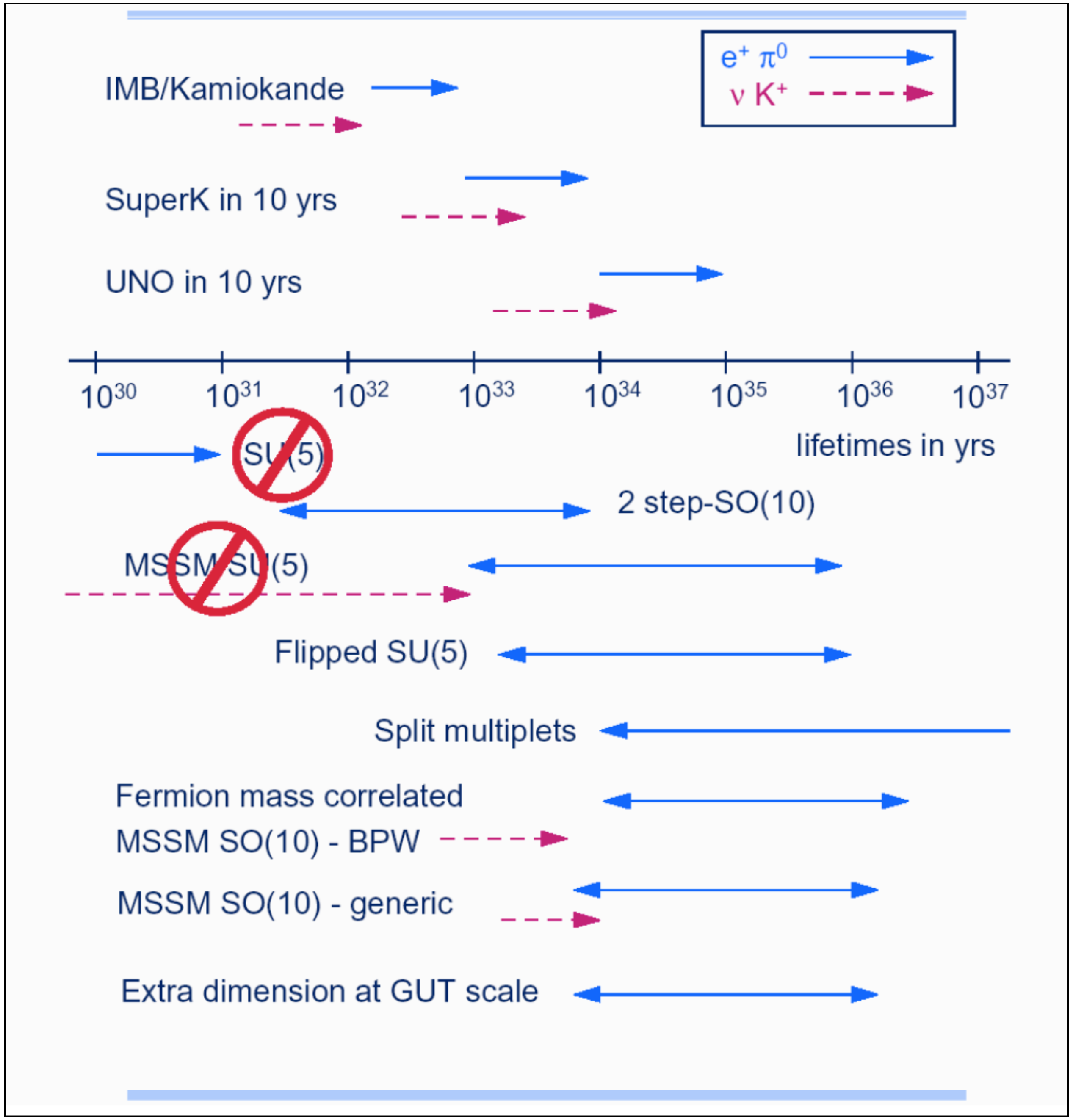
Still, nucleon decay may be "just around the corner"



2003, M. Shiozawa
28th International Cosmic Ray Conference

Future p-decay sensitivity

J. Wilkes, 25 Feb '05
at Neutrino Telescopes



Some |Δ(B–L)|=2 nucleon decay modes (PDG'06+)

(B–L)≠0 modes	Limit at 90% CL	S/B	Experiment'year
$n \to e^- \pi$	$>6.5\times10^{31}$ yr	0/1.6	IMB'88
$n \to \mu^- K^+$	$>5.7\times10^{31}$ yr	0/2.8	Fréjus'91
$p \to e^- \pi^+ \pi^+$	$>3.0\times10^{31}$ yr	1/2.5	Fréjus'91
$n \to \mu^- \pi^+ \pi^0$	$>3.4\times10^{31}$ yr	0/0.78	Fréjus'91
$p \to e^- \pi^+ K^+$	$>7.5\times10^{31}$ yr	81/127	IMB3'99
$p \to \mu^- \pi^+ K^+$	$>2.45\times10^{32}$ yr	3/4	IMB3'99
$n \to \nu\gamma$	$>2.8\times10^{31}$ yr	163/145	IMB3'99
$n \to \nu\gamma\gamma$	$>2.19\times10^{32}$ yr	5/7.5	IMB3'99
$p \to \nu\nu e^+$	$>1.7\times10^{31}$ yr	152/153.7	IMB3'99
$p \to \nu\nu\mu^+$	$>2.1\times10^{31}$ yr	7/11.23	Fréjus'91
$n \to e^+ e^- \nu$	$>2.57\times10^{32}$ yr	5/7.5	IMB3'99
$n \to \mu^+ \mu^- \nu$	$>7.9\times10^{31}$ yr	100/145	IMB3'99
$n \to \nu\nu\bar{\nu}$	$>1.9\times10^{29}$ yr	686.8/656	SNO'04
$n \to \nu\nu\bar{\nu}$	$>5.8\times10^{29}$ yr	0/0.82*	KamLAND'06
$n \to \bar{n}$ *bound*	$>7.2\times10^{31}$ yr	4/4.5	Soudan-II'02

*) accidental background

Theories with $n \leftrightarrow \bar{n}$, no B-L=0 nucleon decay

- Connection with neutrino mass physics via seesaw mechanism

K. Babu and R. Mohapatra, PLB 518 (2001) 269
B. Dutta, Y. Mimura, R. Mohapatra, PRL 96 (2006) 061801

- Connection to low quantum gravity scale ideas

G. Dvali and G. Gabadadze, PLB 460 (1999) 47
S. Nussinov and R. Shrock, PRL 88 (2002) 171601
C. Bambi et al., hep-ph/0606321

- Baryogenesis models at low-energy scale

A. Dolgov et al., hep-ph/0605263
K. Babu et al., hep-ph/0606144

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

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

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

In practice V $\gg \alpha$ for any realistic experiment due to external magnetic fields

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

How to Search for N-Nbar Oscillations

Figure of merit for probability: NT^2

N=total # of free neutrons observed

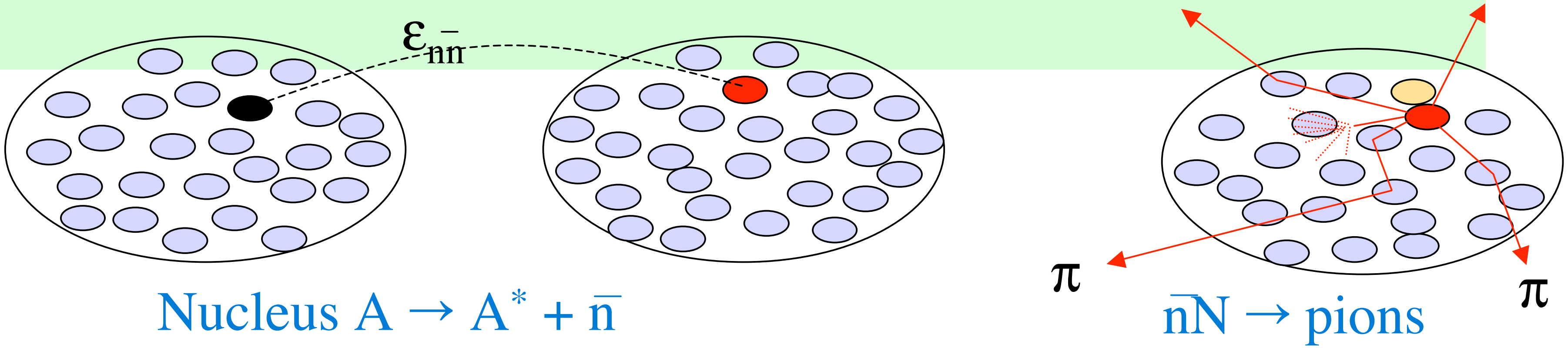
T= observation time per neutron while in "quasifree" condition

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



Suppression of n→nbar in intranuclear transitions from n-nbar potential difference in nuclear matter

Neutrons in nuclei are "quasifree" for $\Delta t \sim \dfrac{1}{E_{binding}} \sim \dfrac{1}{10\,MeV} \sim 10^{-22}\,s$

and experience quasifree condition $N = \dfrac{1}{\Delta t}$ times per second,

transition rate is $P_A = \left(\dfrac{\alpha t}{\tau_{n\bar{n}}}\right)^2 \times \left(\dfrac{1}{\Delta t}\right)$

Intranuclear transition lifetime: $\tau_A = \boxed{\dfrac{\tau_{n\bar{n}}^2}{\Delta t} = R \times \tau_{n\bar{n}}^2,}$ $R \sim \dfrac{1}{\Delta t} \sim 10^{22}\,s^{-1}$

Calculations for ${}^{16}O, {}^{2}D, {}^{56}Fe, {}^{40}Ar$ by Dover et al, Alberico et al,
Kopeliovich et al. are consistent, give order of magnitude greater suppression
Thus, e.g. Soudan - 2 limit $\tau_{Fe} > 7.2 \times 10^{31}\,yr$ corresponds to $\tau_{n\bar{n}} > 1.3 \times 10^{8}\,s$

Example: Soudan 2

- Soudan 2 is located in the Soudan mine in Northern Minnesota under 2100 mwe overburden.
- Data-taking: April 1989 to June 2001.
- Analyzed exposure is 5.56 fiducial kiloton-years

Conclusion(Tony Mann, NNbar conference, 2002):

Limit for nnbar oscillations in iron (90% confidence):

$$T_A(\text{Fe}) > 7.2 \times 10^{31} \text{ years}$$

Corresponding limit on oscillation time (assuming $T_R = 1.4 \times 10^{23}$ s)

$$\tau_{n\bar{n}} > 1.3 \times 10^{8} \text{ seconds.}$$

Background arising from multiprong interactions of atmospheric neutrinos is observed: ~ 0.7 ν evts/kty.

SNO and SuperK can achieve $\tau_{nn} > (4 - 5) \times 10^{8}$ sec. Harder to make discovery in presence of neutrino background

Extending search limit sensitivity beyond $\tau_{nn} = 10^{9}$ secs requires a different approach.

SNO's Advantages

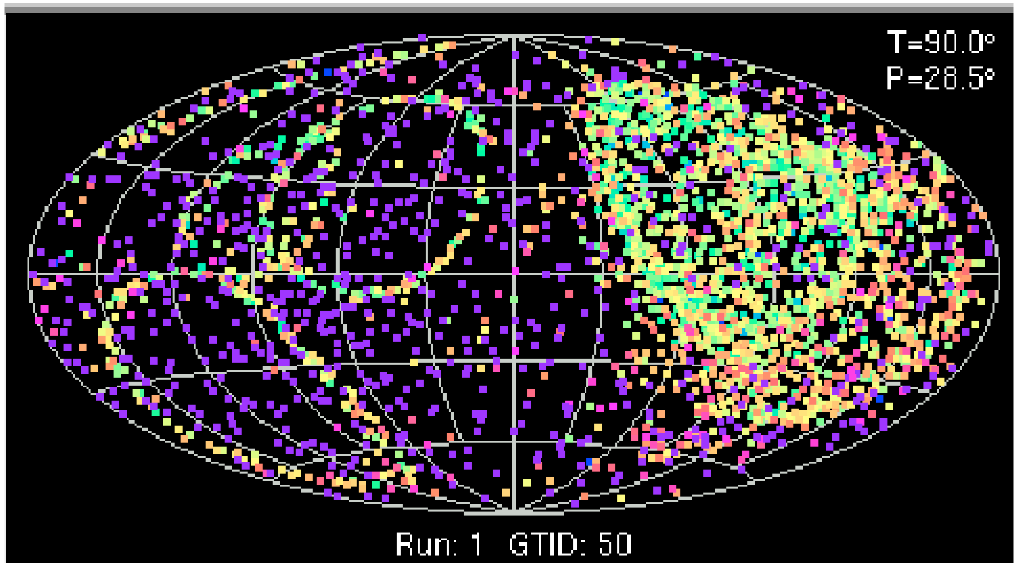
- Though much smaller than Super-K, SNO has advantage of conventional proton decay experiments for neutron oscillations:
  - Background. Smaller inherent background from cosmic rays and atmospheric neutrinos.
  - Target material. Deuterium has smaller correction factor than O^{16} and thus favors neutron oscillation processes.

Nucleus	Model 1	Model 2
^{2}H	$0.25 \times 10^{23} s^{-1}$	$0.24 \times 10^{23} s^{-1}$
^{16}O	$1.20 \times 10^{23} s^{-1}$	$0.80 \times 10^{23} s^{-1}$
^{56}Fe	$1.13 \times 10^{23} s^{-1}$	$1.69 \times 10^{23} s^{-1}$

[3] C.B. Dover et al., Phys. Rev. D27, 1090 (1983).

Neutron Oscillation Limits

- SNO offers 1kton of D_2O
- Low atmospheric rate
  - $\sim$ 100 ν_μ events / year
- Clean signature?
  - ^2H : multi-pion rings
  - ^{16}O : neutron followers
- Energy calibration
  - Use muons through-going and stopped.



$$\tau_{SNO} = (1\text{-}2 \times 10^8 \text{ s})\, t^{1/2}$$

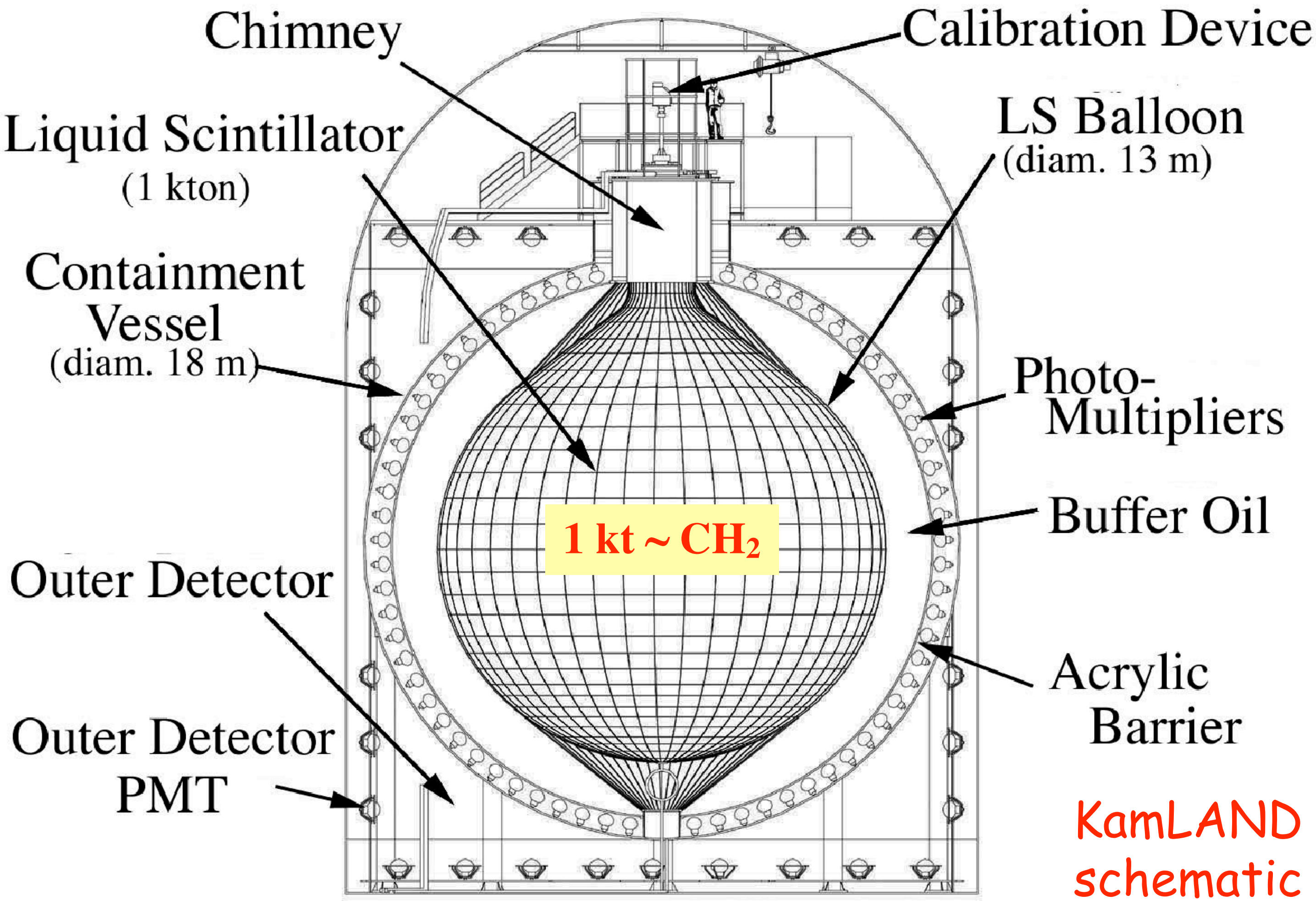
Searches for Baryon non-conservation in KamLAND

n and nn

disappearance :

e.g. $n \to \nu\nu\bar{\nu}$

$nn \to \nu\nu$



KamLAND schematic

Unique features of KamLAND detector:

- Large mass: 1,000 ton of Liquid Scintillator (~ CH_2)
- Low detection threshold: < 1 MeV
- Good energy resolution $\sim 7\% / \sqrt{E(MeV)}$
- Position reconstruction accuracy in x,y,z: ~ 15 cm
- Low background: 2700 mwe; buffer shield; veto-shield;

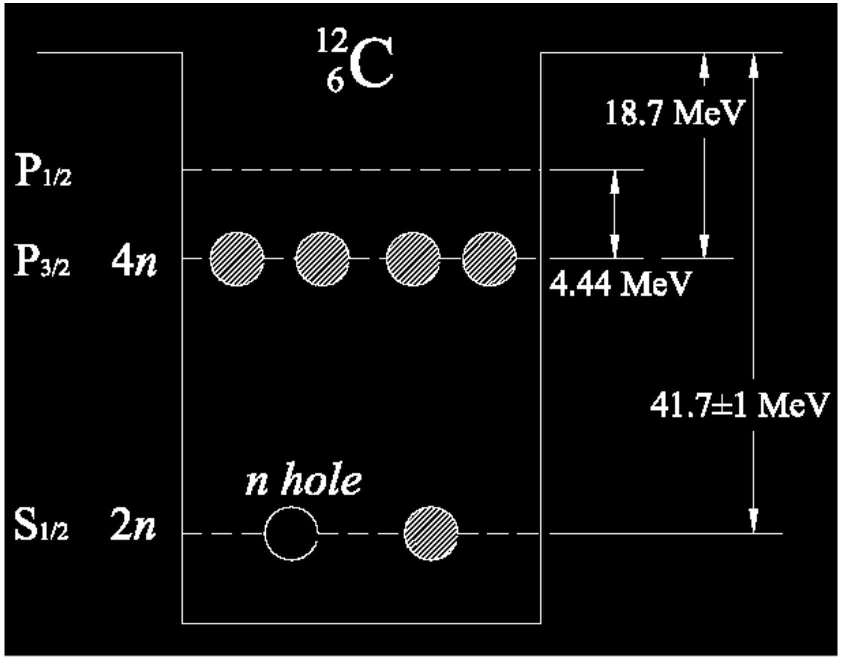
  Rn shield; LS purification for U, Th < 10^{-16} g/g

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

Measurement idea:

SIGNATURES OF NUCLEON DISAPPEARANCE IN LARGE UNDERGROUND DETECTORS. Edwin Kolbe and YK
Phys.Rev.D67:076007, 2003

$$^{12}C \rightarrow n\left(in \;\; s_{1/2} \;\; state \;\; disappeared\right) + {}^{11}C^*\left(excited\right)$$



$$^{11}C^* \rightarrow de-excitation \;\; particles$$

$$+ \hat{a}-decay \;\; of \;\; daughter \;\; nucleus$$

Search for the sequence
of events (≥3 hits)
correlated in space and time

2 neutrons out of 6 in ^{12}C
are is $s_{1/2}$ state

n→nbar search limits with bound neutrons

$$\text{Soudan-2 limit: } \tau_{Fe} > 7.2\times10^{31}\ \textit{years}$$

$$S/B = 4/4.5$$

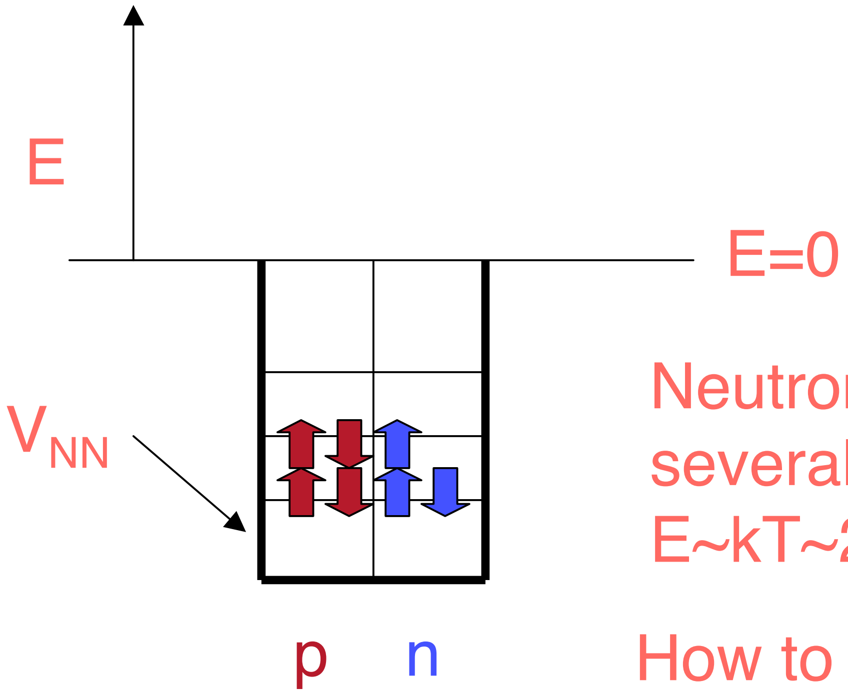
Future potential limits expected from SNO and Super-K

$$\text{SNO:} \quad \tau_D \sim 4.8\times10^{32}\ \textit{years}$$

$$\text{Super-K:} \quad \tau_O \sim 7.5\times10^{32}\ \textit{years}$$

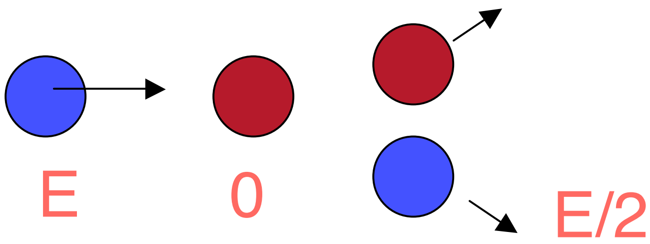
Since sensitivity of SNO, Super-K, and future large underground detectors will be limited by atmospheric neutrino background (as demonstrated by Soudan-2 experiment), it will be possible to set a new limit, but difficult to make a discovery!

Why is it such hard work to get slow neutrons (or antineutrons)?



Neutrons are bound in nuclei, need several MeV for liberation. We want E~kT~25 meV (room temperature) or less

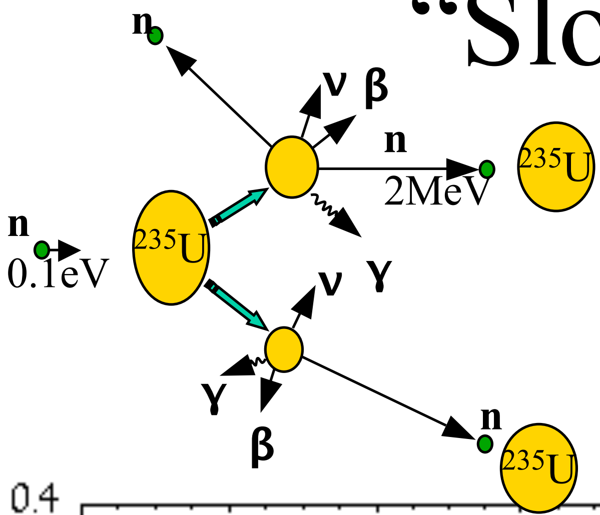
How to slow down a heavy neutral particle with $M_n = M_p$? Lots of collisions…



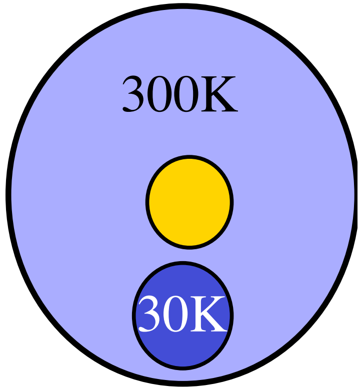
$[1/2]^N$=(1 MeV)/(25 meV) for N collisions

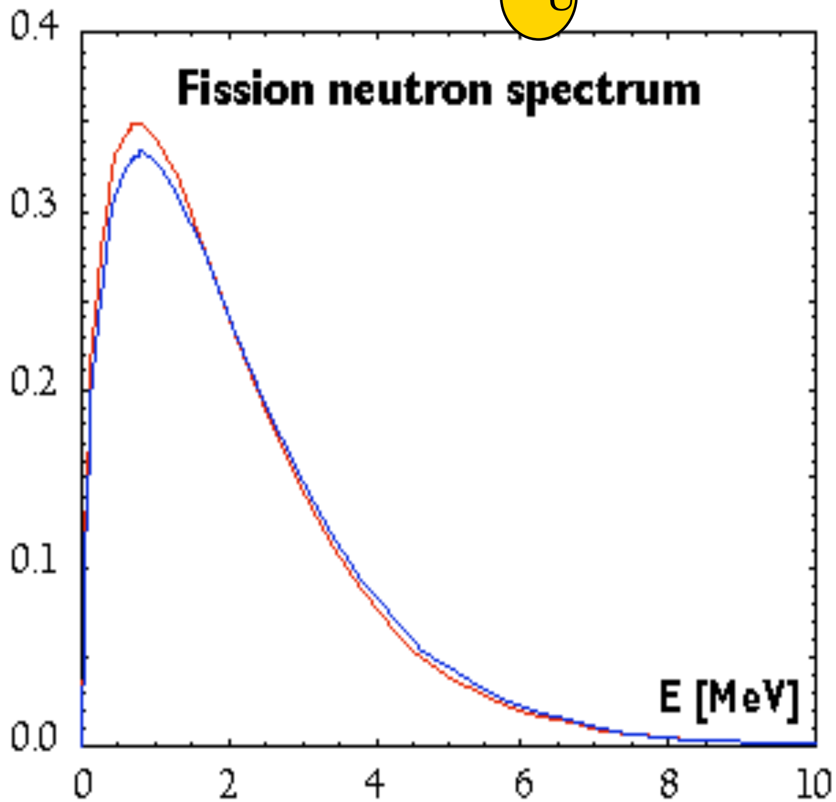
Neutrons are unstable when free->they can't be accumulated easily

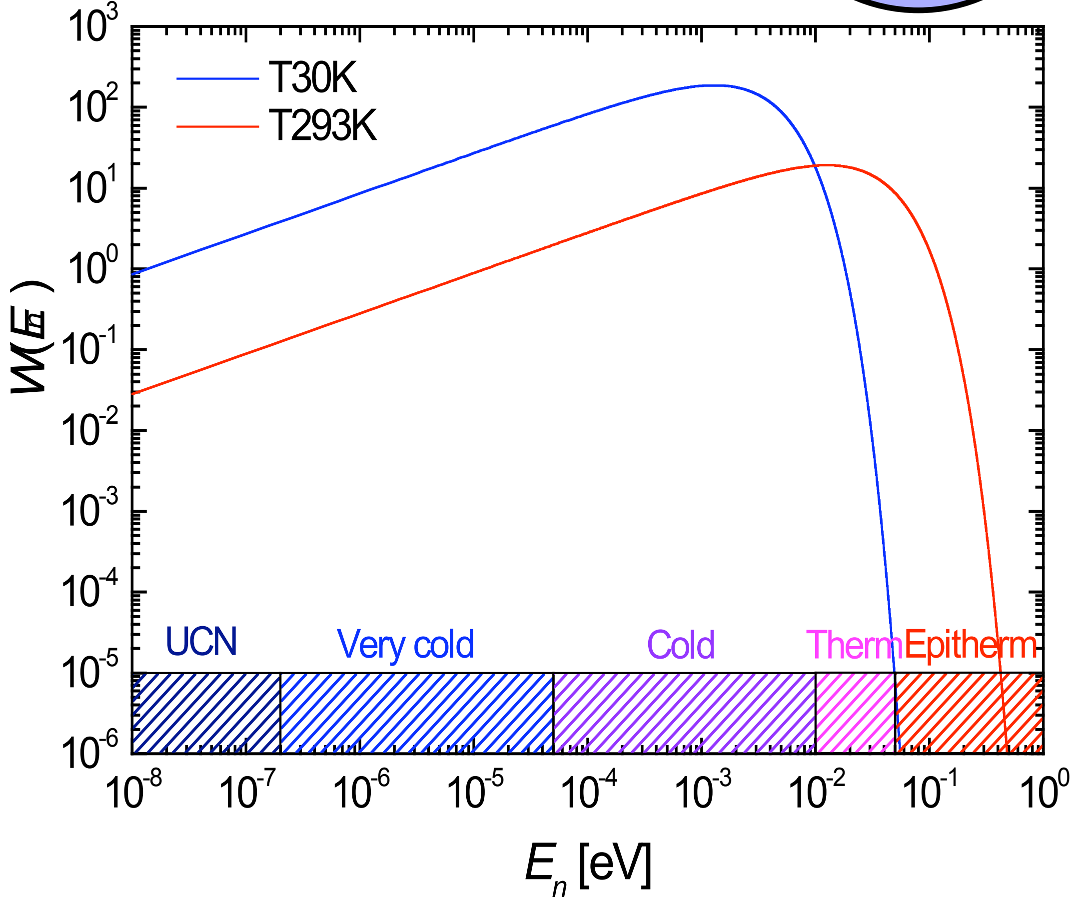
“Slow” Neutrons: MeV to neV



Nuclear reactor







Source and Neutron Moderator

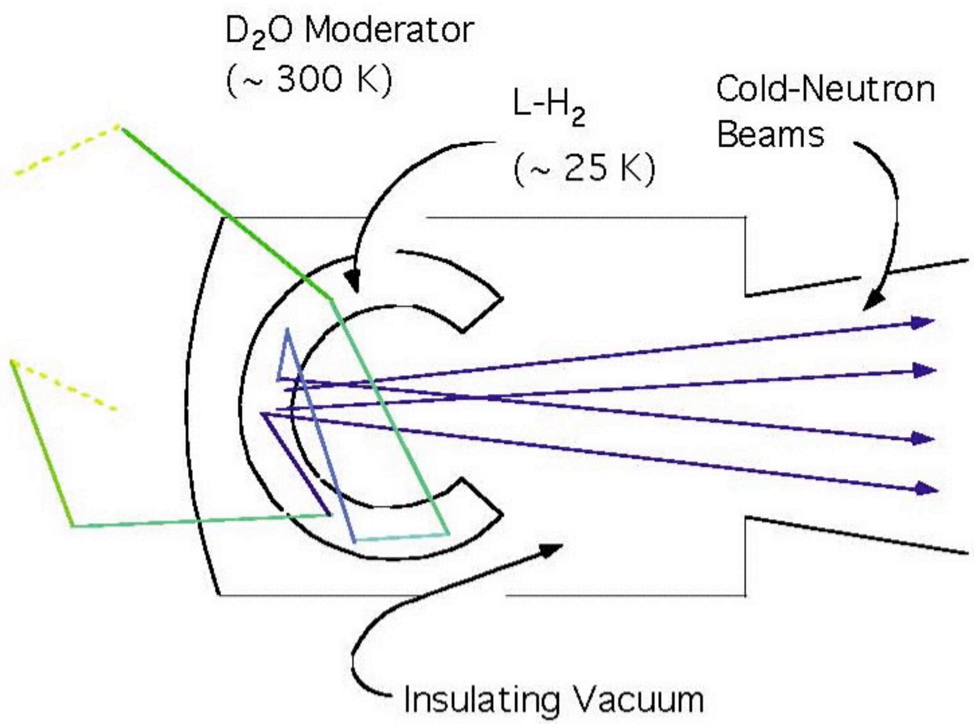
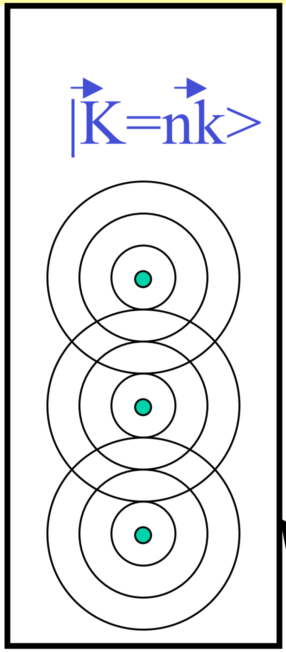


Figure 7. A cavity-type cold moderator. Thermal neutrons (green) enter the 25-K liquid hydrogen from the 300-K D_2O moderator. There, they collide numerous times, losing energy at each collision (less green), and come into equilibrium with the hydrogen at 25 K (blue). The reentrant cavity acts as a hohlraum, *allowing neutrons to rattle around within, promoting thermal equilibration but permitting cold neutrons to emerge efficiently into the neutron beams. The diagram exaggerates the thickness of the $L\text{-}H_2$ layer in relation to the diameter of the cavity and omits the necessary plumbing arrangements.*

Neutron Optics

$|\vec{k}\rangle$ $\quad |\vec{K}=n\vec{k}\rangle$ $\quad e^{i\phi}|\vec{k}\rangle$



kR>>1

s-wave

$f_{scatt}=b$

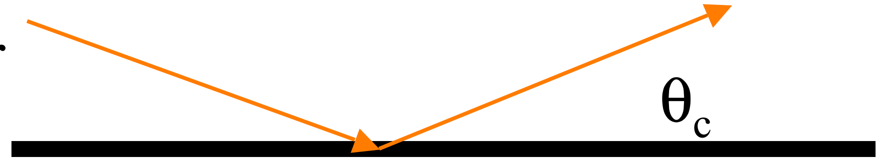
L

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

Index of refraction

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

matter



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

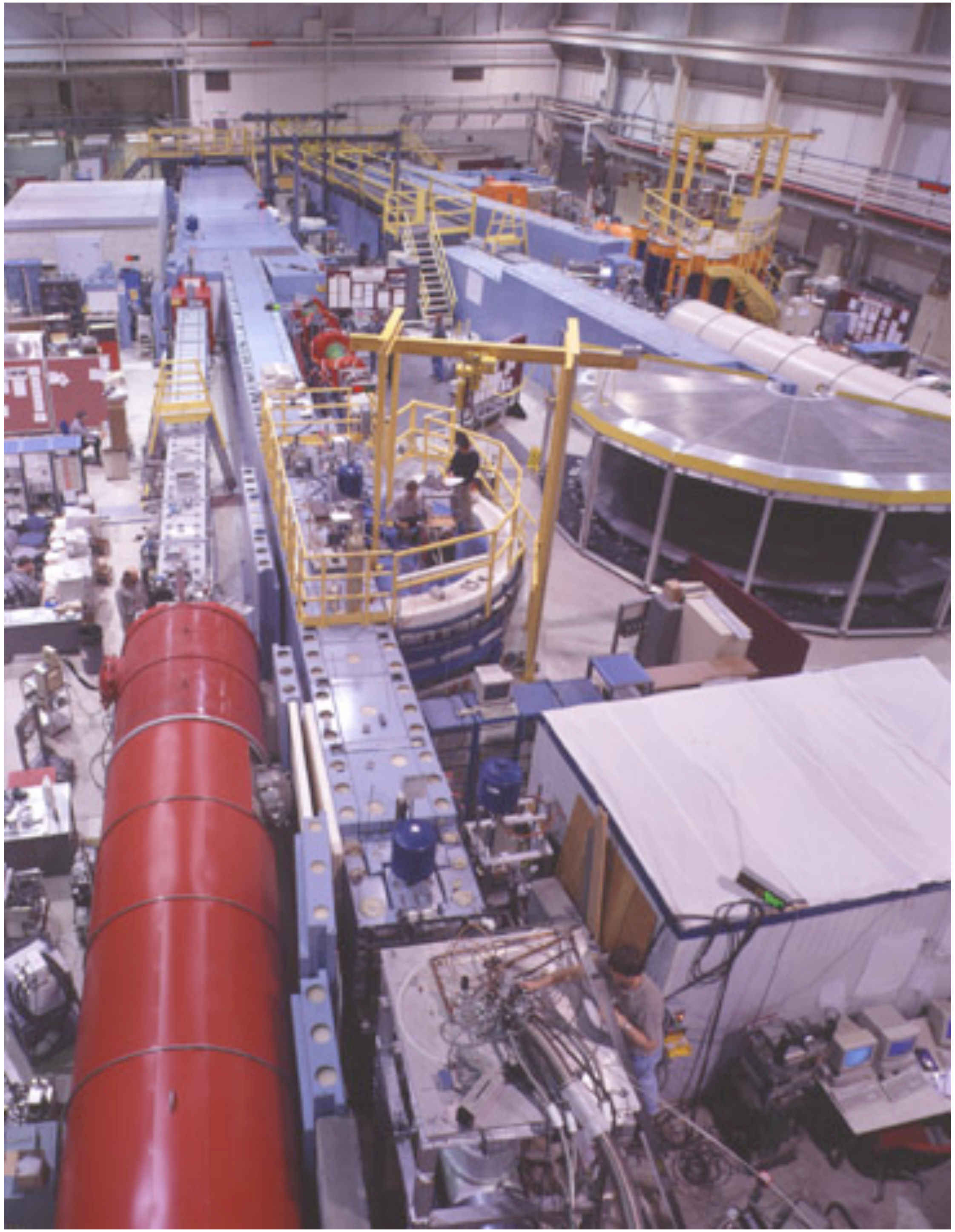
$\langle V_{strong}\rangle=2\pi h^2\rho b_s/m$, ~+/- 100 neV

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

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

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

For $E_k-\langle V\rangle$ negative, neutron reflects from the optical potential

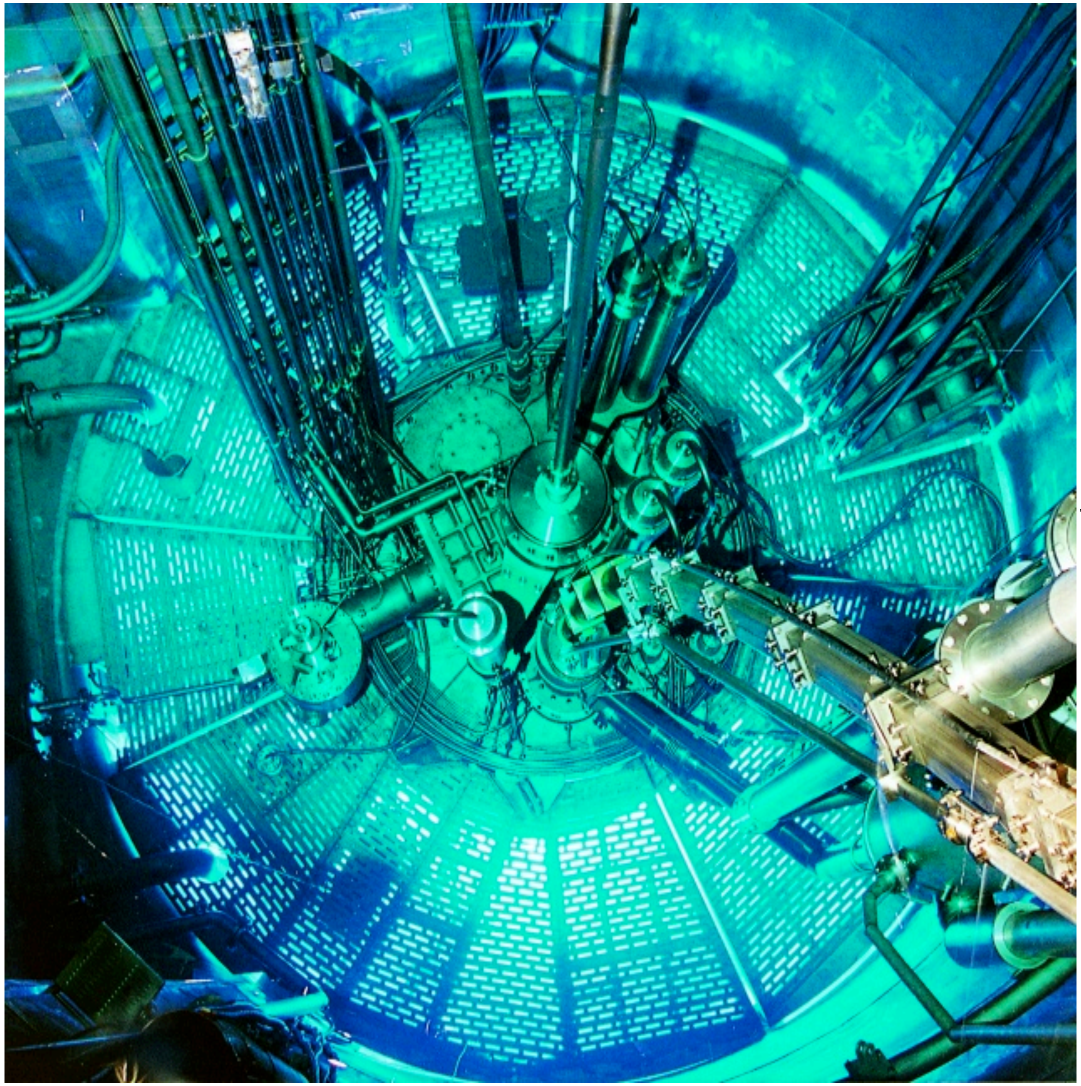


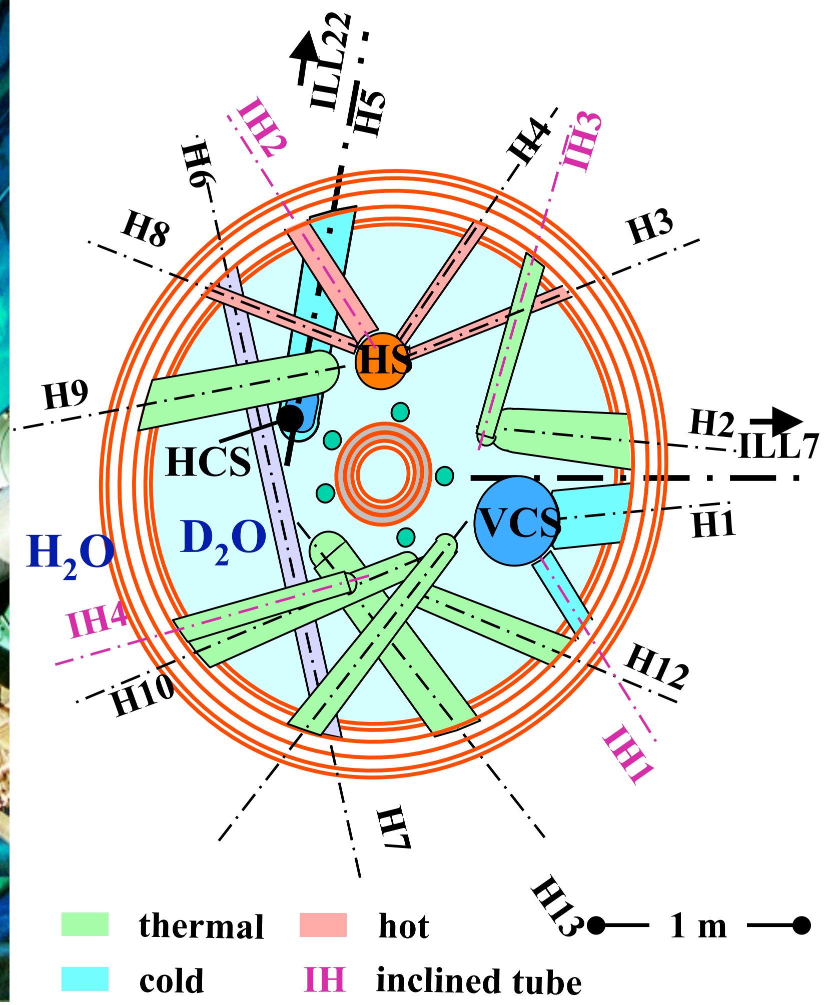
NIST Cold Neutron Guide Hall

Reactor makes neutrons, cooled to ~20K by liquid hydrogen

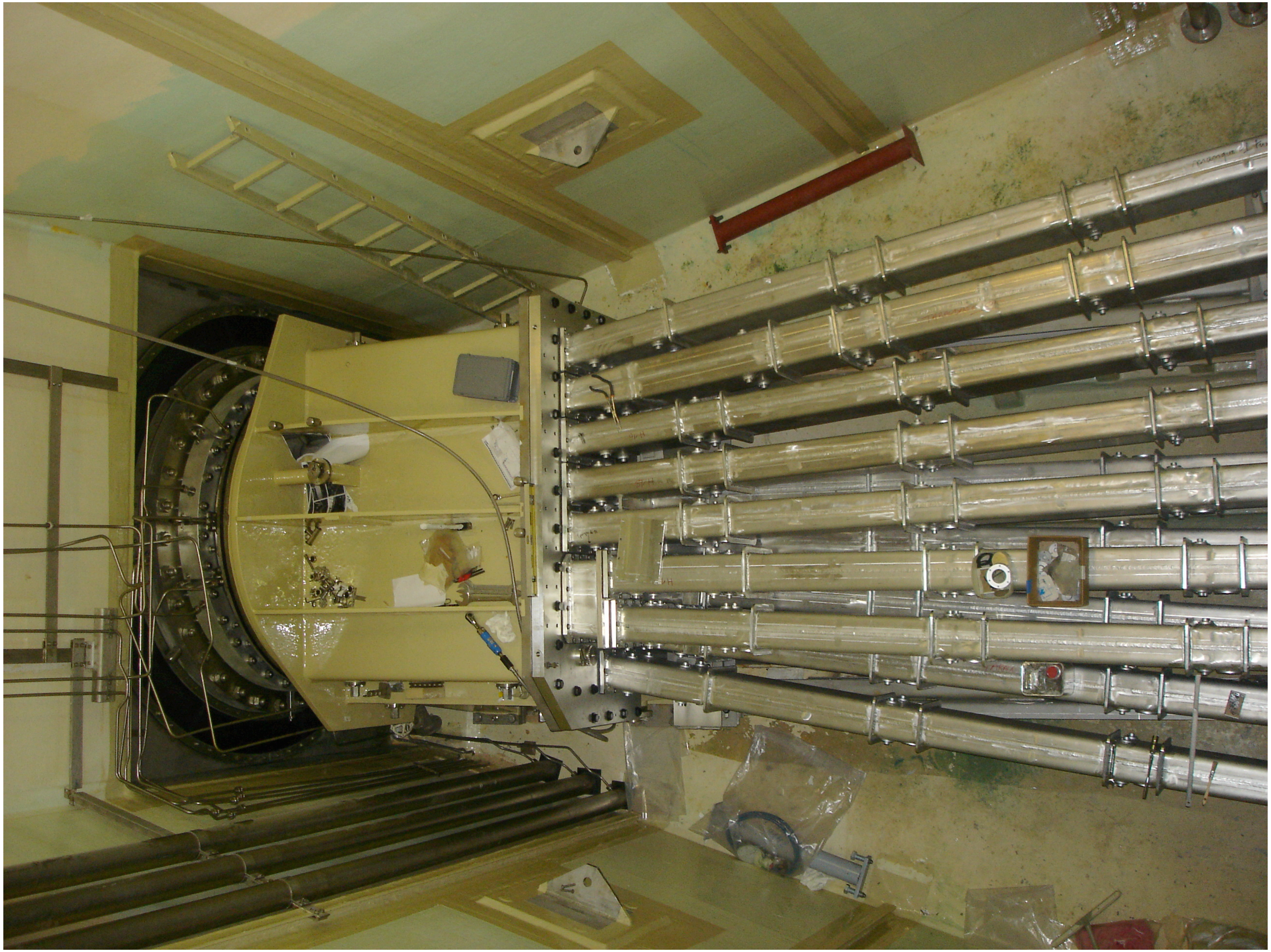
Neutron mirrors ("guides") conduct the neutrons ~100 meters with small losses.

Inside the ILL Reactor

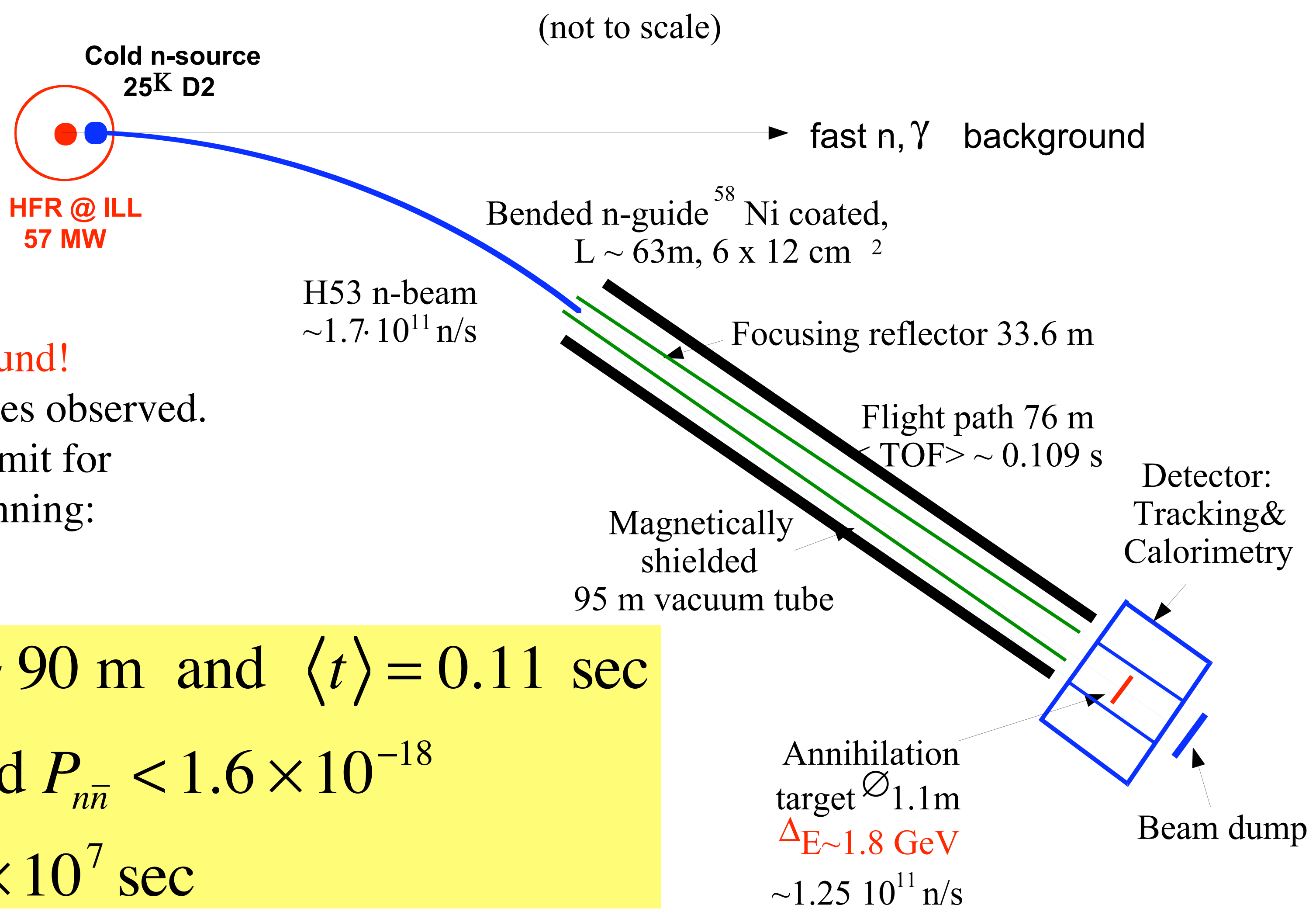




Neutron guides at ILL (top view)



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



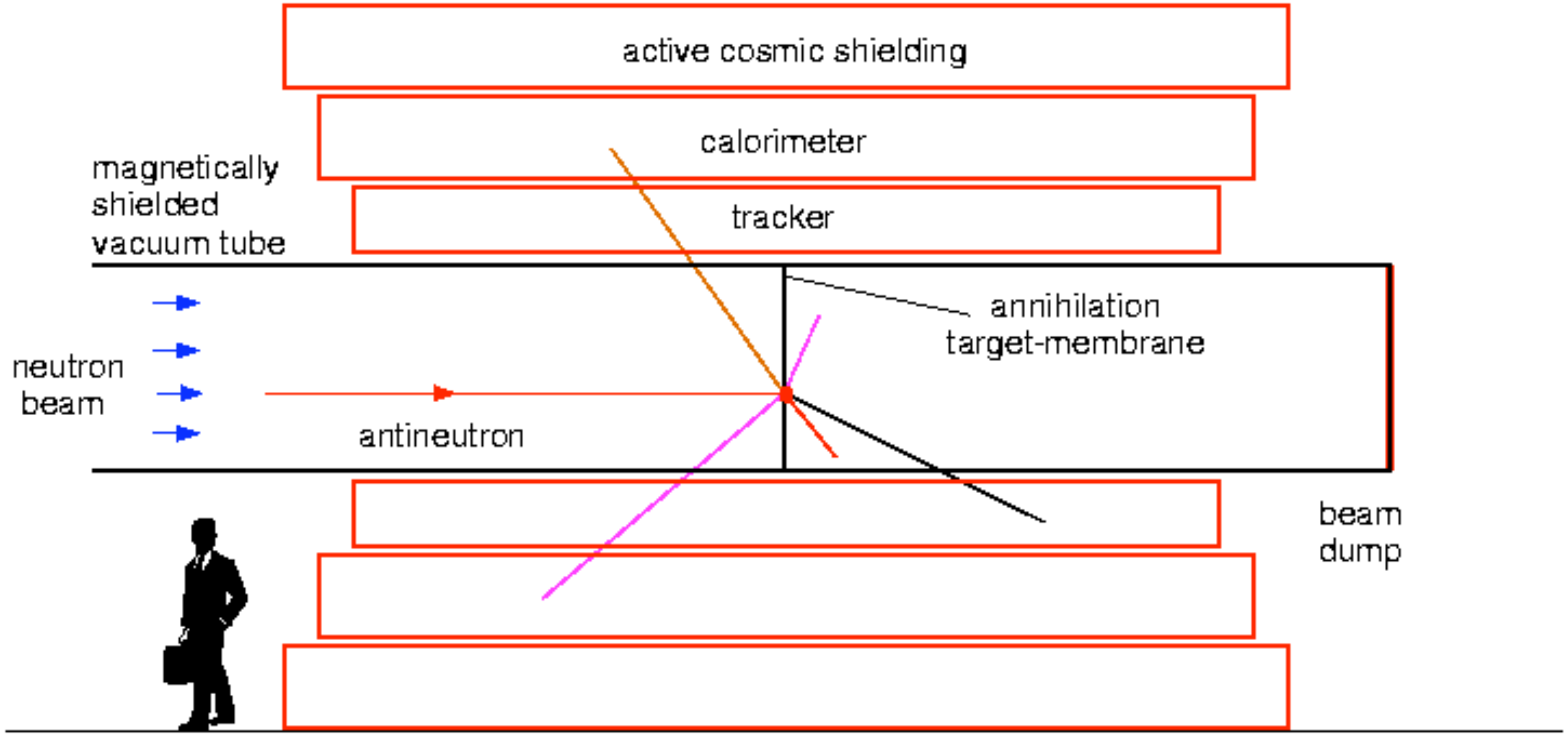
No background!
No candidates observed.
Measured limit for
a year of running:

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

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

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

The conceptual scheme of antineutron detector



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

Annihilation target: ~100μ thick Carbon film

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

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

N-bar annihilation vertex precisely defined by absorption in thin carbon foil ->background suppression

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

= 1 unit of sensitivity

Volume 236, number 1 PHYSICS LETTERS B 8 February 1990

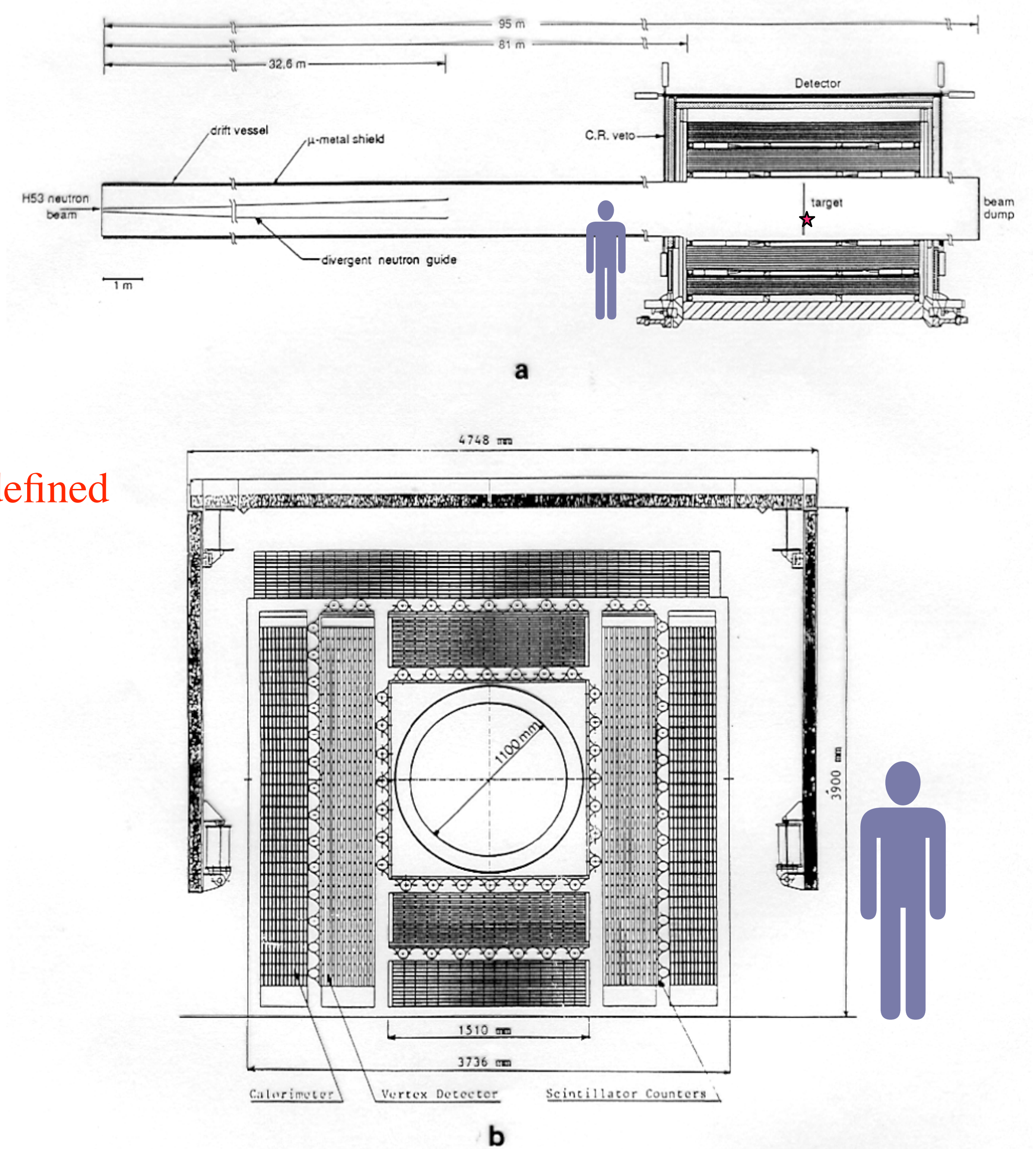


Fig. 1. (a) Experimental apparatus showing the "quasi free" neutron propagation length with the divergent guide, the target and the detection system. (b) Cross sectional view of the detector.

Neutron Reflector Using Multilayers

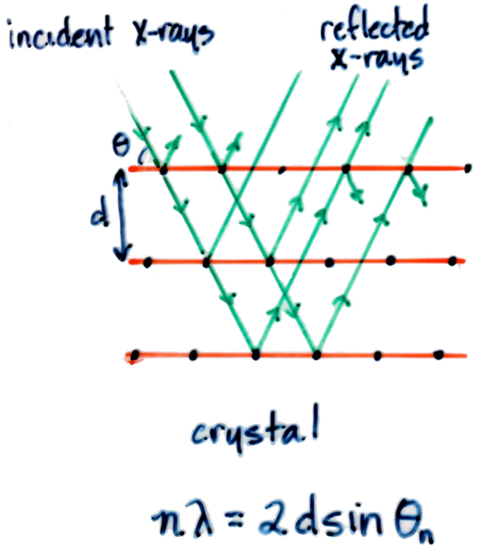
Graded multilayers operate on the principle of Bragg reflection

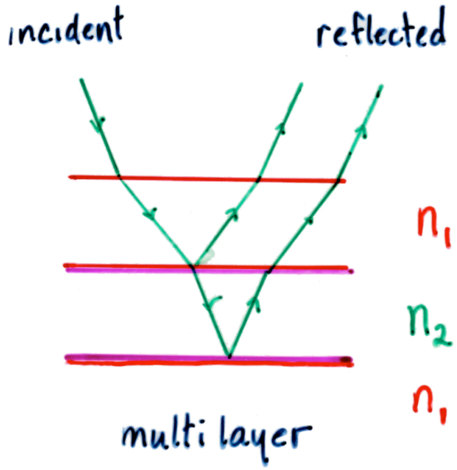
alternating layers of low and high index of refraction

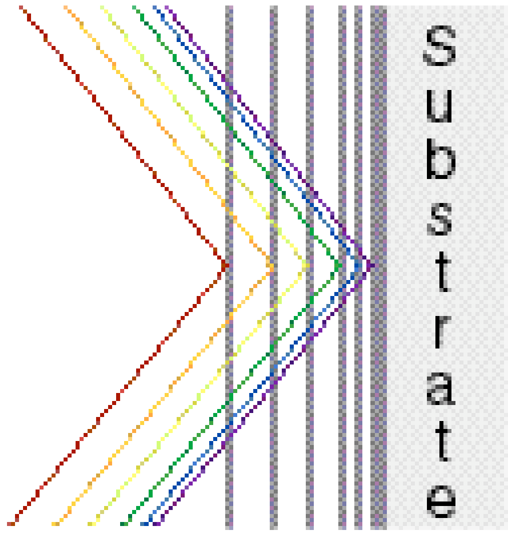
$n\lambda = 2d\sin\theta$ d = bilayer thickness

Wide range of bilayer thickness provides broadband reflectance

We need to make a large elliptical reflector. Neutrons only bounce once-> reflectivity not crucial



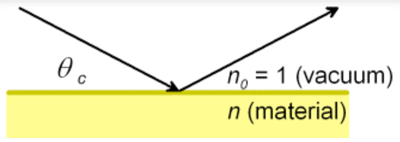




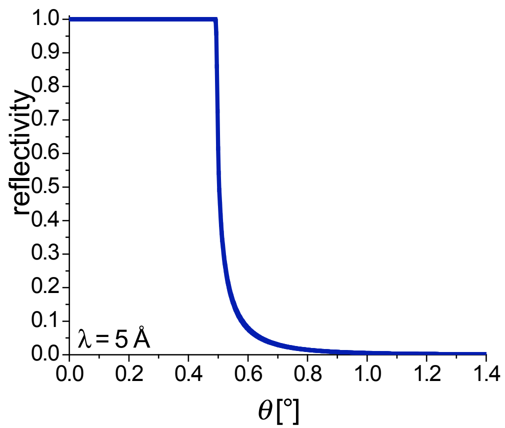
concept of neutron supermirrors: Swiss Neutronics

neutron reflection at grazing incidence (< ≈2°)

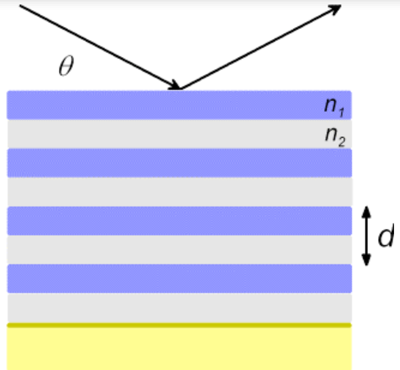
@ smooth surfaces



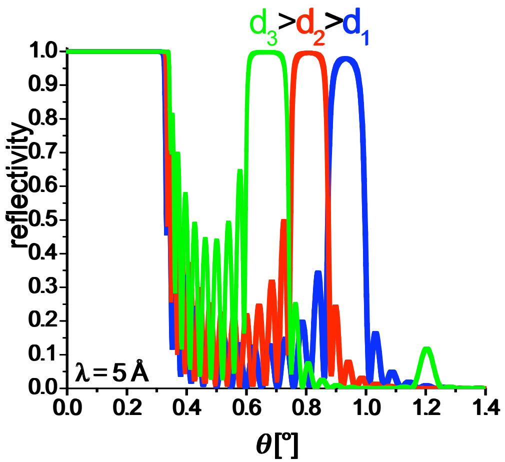
- refractive index n < 1
- total external reflection e.g. Ni θ_c = 0.1 °/Å



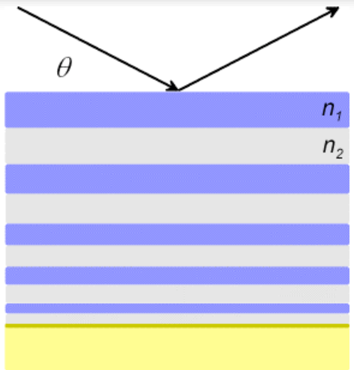
@ multilayer

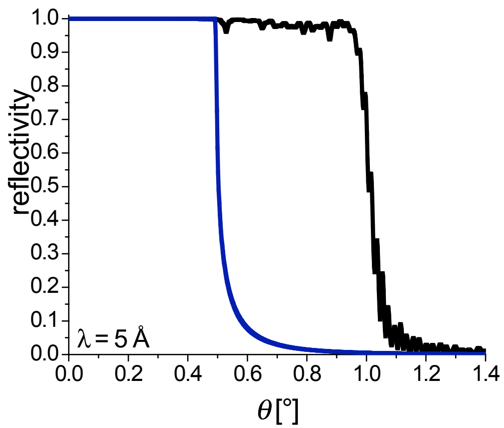


$$\lambda = 2d\sin\theta$$



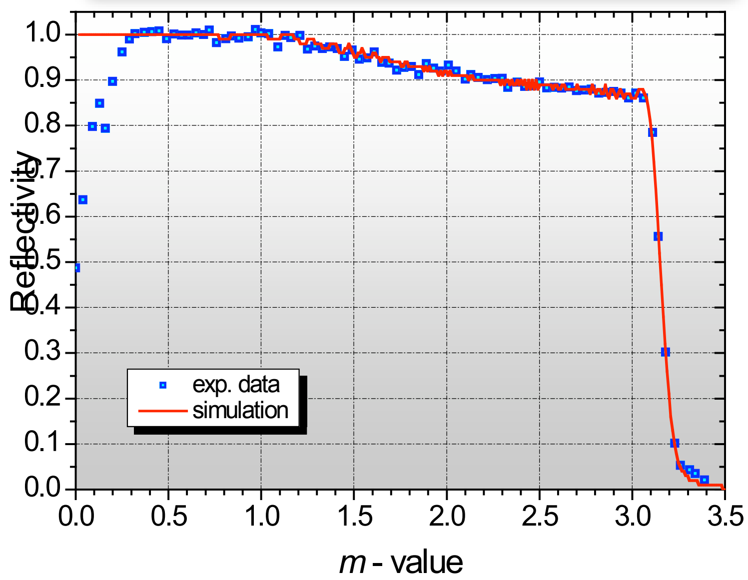
@ supermirror

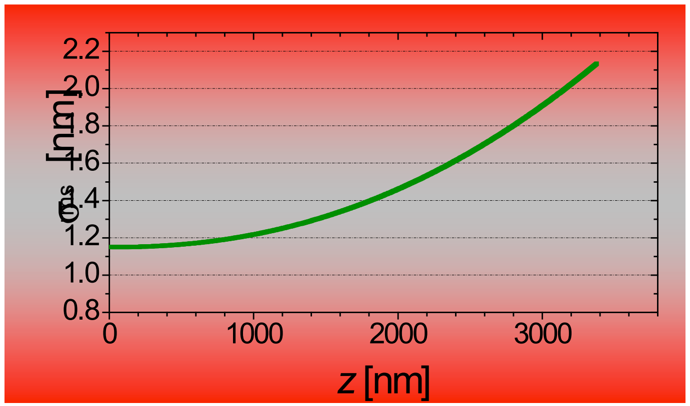




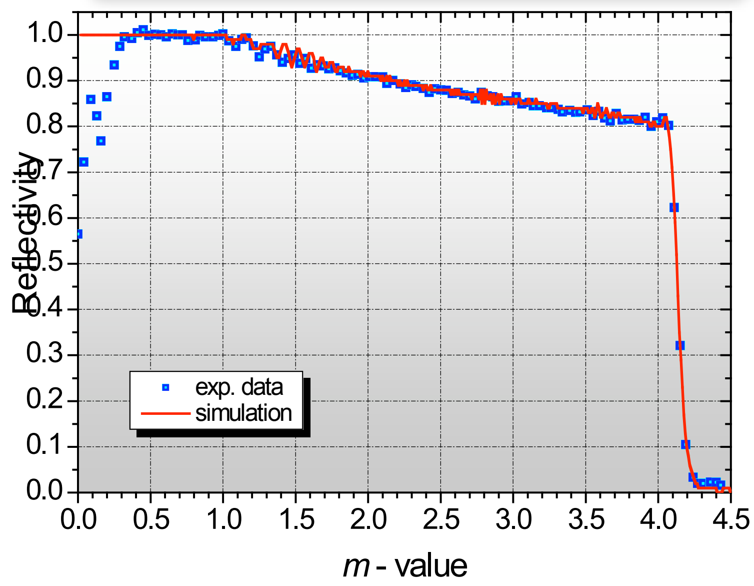
Ni/Ti supermirrors – high 'm' : *Swiss Neutronics*

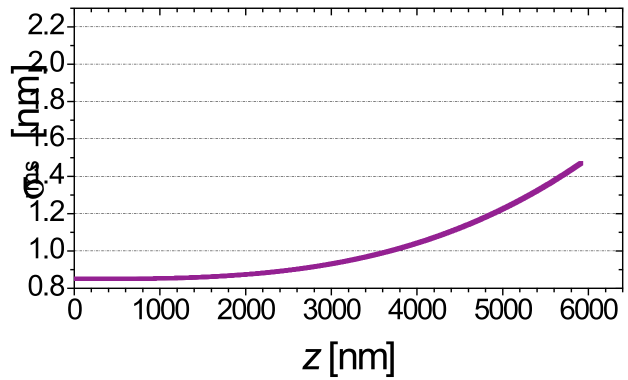
***m* = 3**





***m* = 4**





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

Supermirror Neutron Optics: Elliptical Focusing Guides

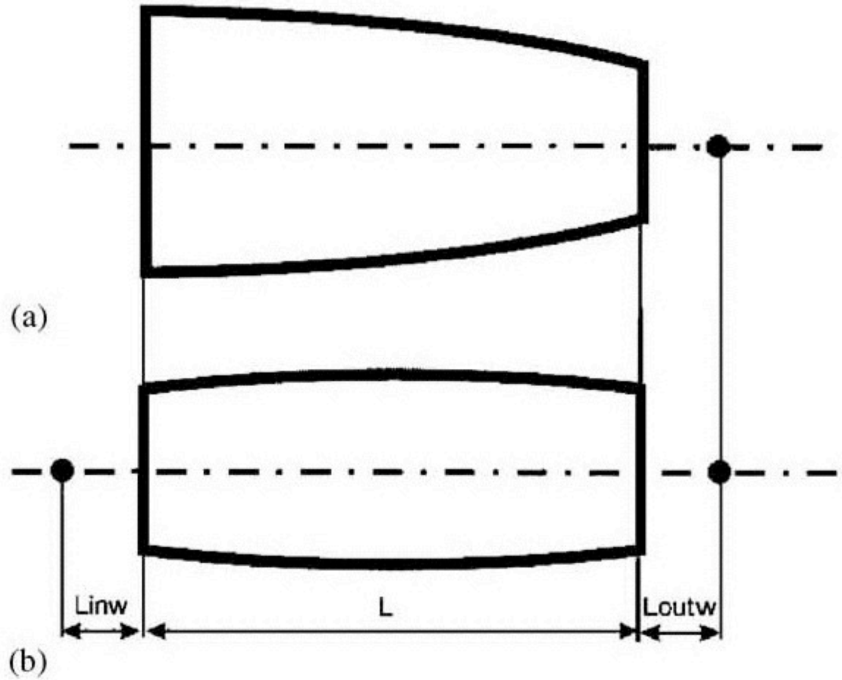


Fig. 1. Parameters for the (a) parabolic and (b) elliptic focusing guide in the x-plane.

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

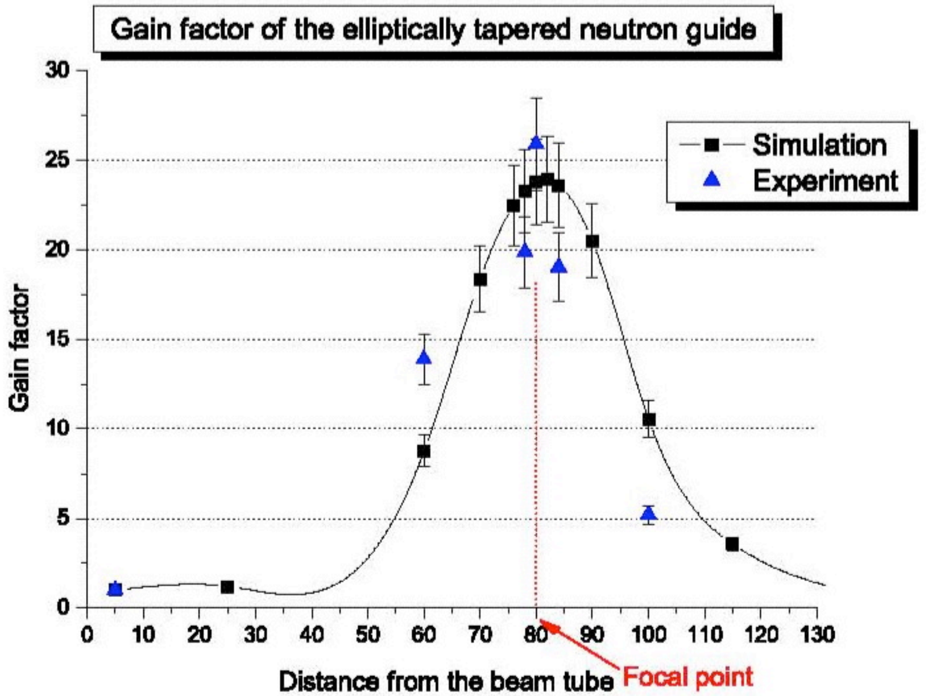


Fig. 3. Neutron intensity as measured and calculated versus distance from the exit of the guide. Clearly seen is the point of maximum intensity near $F_2 = 80\,\mathrm{mm}$.

Under development for neutron scattering spectrometers

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

Why Focusing Reflector?

In a simple geometry without focusing
with neutron velocity v_n , flux F, detector of area A, and distance source-detector L:

$$N_n \propto F \cdot d\Omega = F \cdot \frac{A}{L^2}; \qquad < t^2 > \approx \frac{L^2}{v_n^2}; \qquad \text{and} \qquad F \propto v_n$$

$$Sensitivity = N \cdot < t^2 > \propto F \cdot \frac{A}{v_n^2} \propto \sqrt{T_n} \cdot \frac{A}{T_n} = \frac{A}{\sqrt{T_n}}$$ ←does not depend on L

With focusing reflector: fraction of neutron flux within the fixed solid angle is intercepted by single reflection and directed to the detector.

$$d\Omega = const; \quad \text{reflector interception efficiency} \propto \frac{1}{T_n}$$

$$Sensitivity \propto \frac{d\Omega \cdot L^2}{T^{3/2}}$$ ← major source of sensitivity improvement

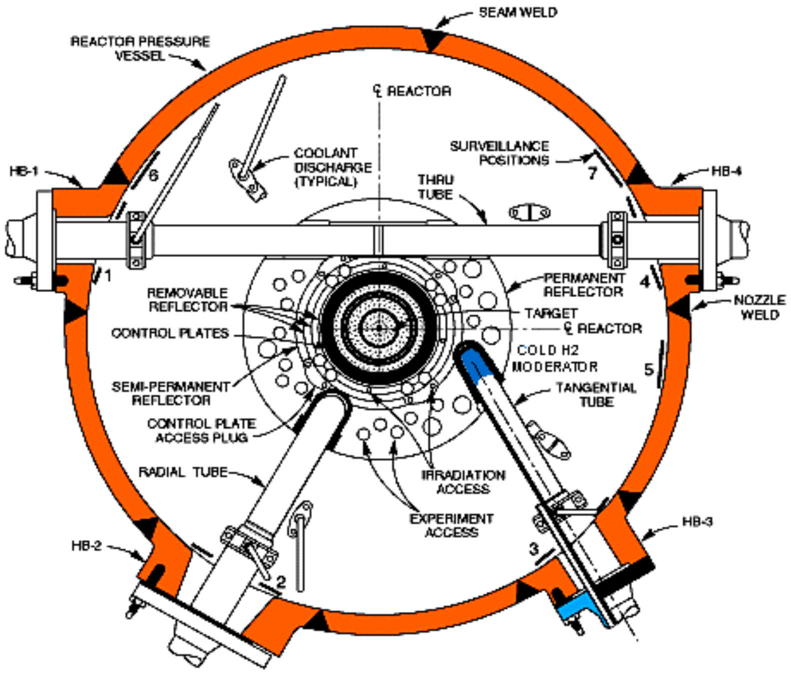
Searches with cold neutrons: looking for a reactor…

- possible to increase sensitivity to transition probability by ~ 1,000

  $\tau_{bound} > 10^{35}$ years; $\tau_{free} > 10^{10}$ sec

- need close access of focusing reflector to cold neutron source at high flux reactor

- use existing research reactor facilities? No luck so far (NIST? FRM?)



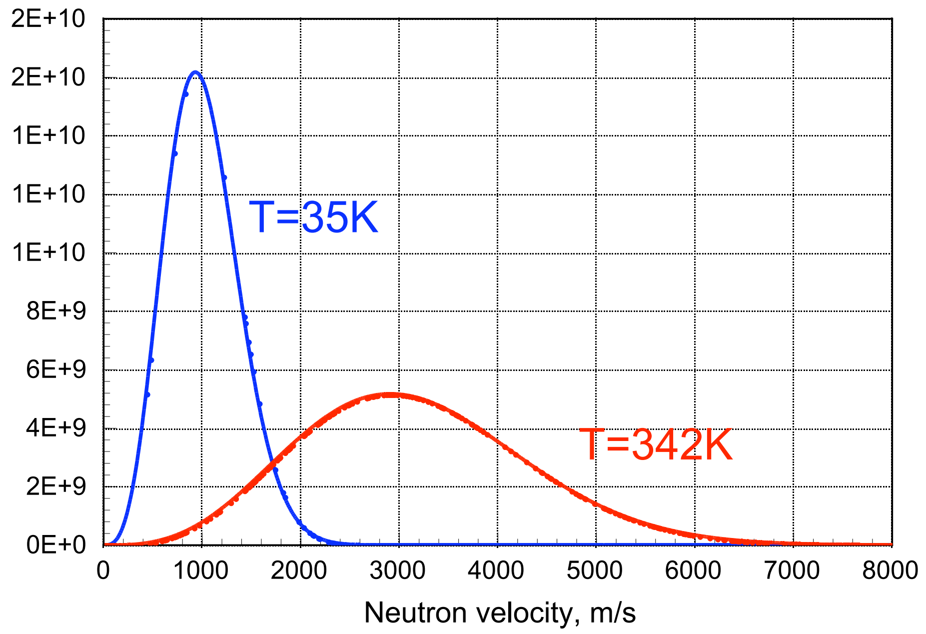
Need max flux and max observation time!

E of reactor fission neutrons ~ 2 MeV

E of thermal (300 K) neutrons ~ 0.025 eV

<V> of thermal neutrons ~ 2200 m/s

<V> of Cold neutrons ~ 1000 m/s



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

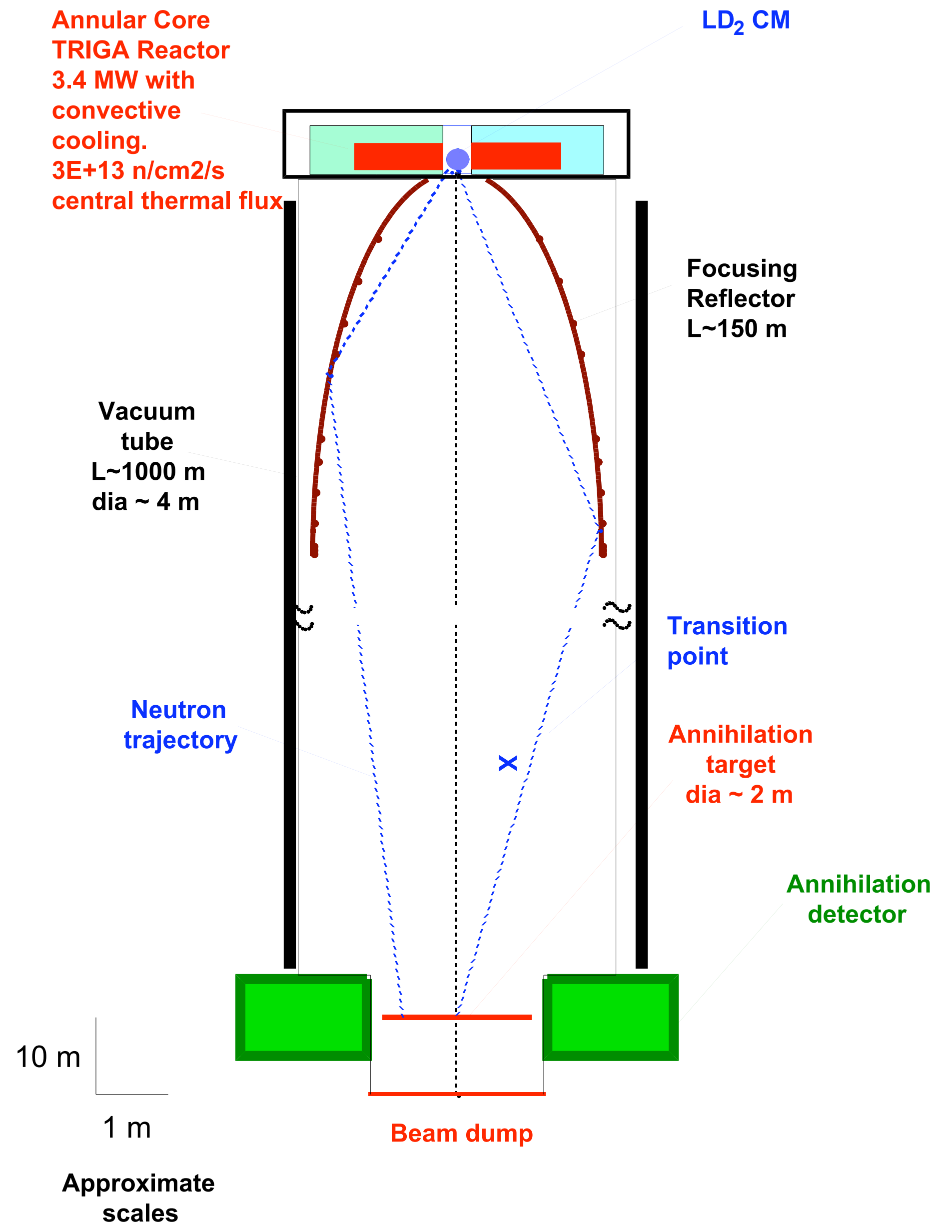
→ Vertical beam layout preserves all the cold spectrum and allows max path length

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 the shaft (no new technologies)



HOMESTAKE DUSEL

Deep Underground Science and Engineering Laboratory

February 9, 2006 at Lead, SD Workshop (LOI #7)

May 5, 2006 SUNY Stony Brook workshop

Search for neutron → antineutron transitions at DUSEL

N-Nbar proto-collaboration

D. Baxter[2], W. Bugg[8], Y. Efremenko[8], A. Fomin[7], T. Gabriel[8], K. Ganezer[1], T. Handler[8], T. Ito[3], Y. Kamyshkov[8], A. Kharitonov[7], A. Kozlov[8], M. Leuschner[2], C-Y. Liu[2], V. Mityukhlyaev[7], R. Mohapatra[4], P. Mumm[6], A. Serebrov[7], G. Shmelev[7], W. M. Snow[2], S. Spanier[8], A. Young[5], C.West[8], A. Young[5], B. Wehring[5], A. Zakharov[7]

[1] *California State University, Domingues Hills*
[2] *Indiana University*
[3] *Los Alamos National Laboratory*
[4] *University of Maryland*
[5] *North Carolina State University*
[6] *NRC/NIST*
[7] *St. Petersburg Nuclear Physics Institute, Russia*
[8] *University of Tennessee*

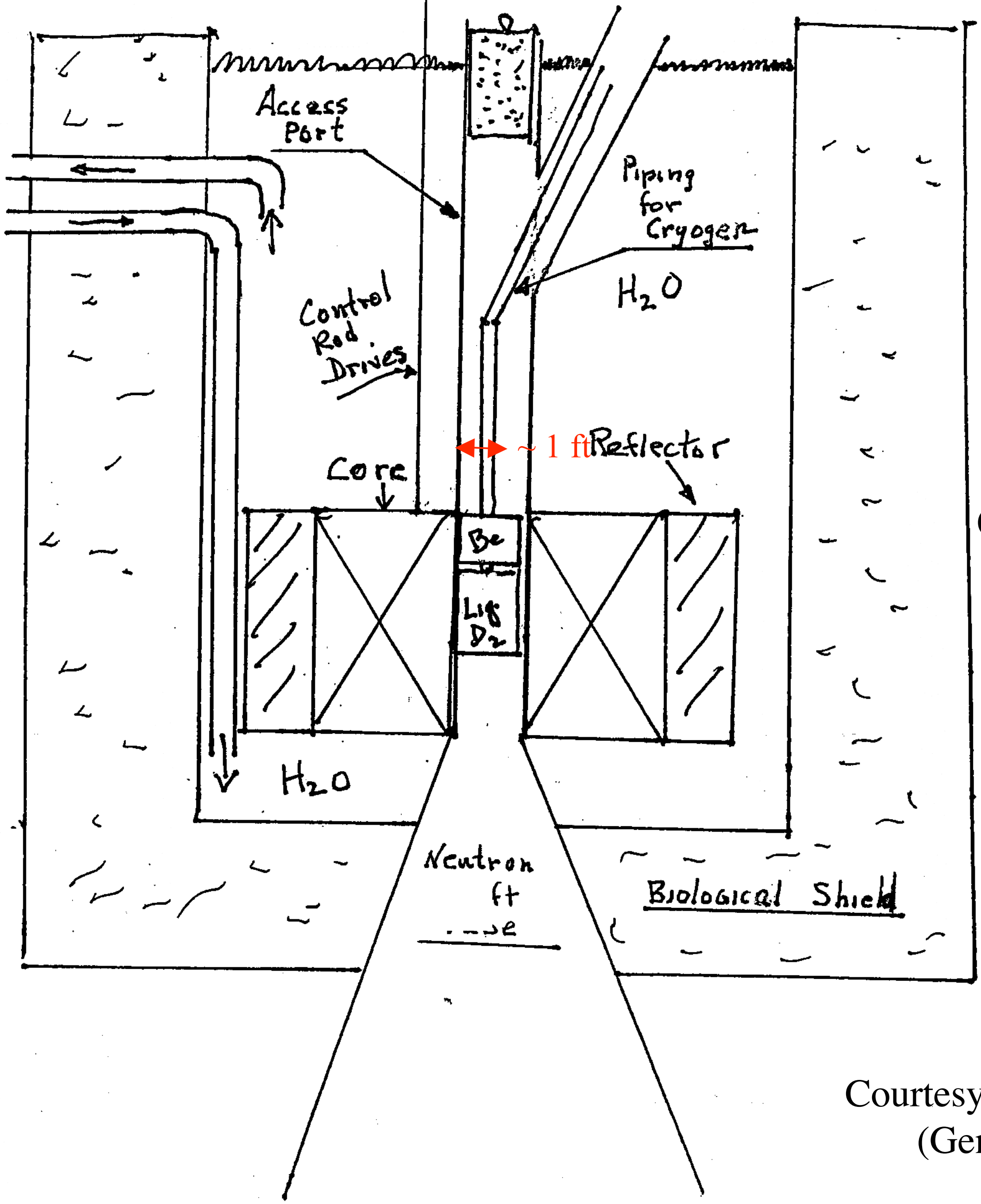
(Contact address: Yuri Kamyshkov <kamyshkov@utk.edu>)

(continued)

2.6.2 Recommendation

The Program Advisory Committee finds this proposal of significant scientific merit, and endorses consideration as a long-range possibility for DUSEL. For the Early Implementation Program, the PAC recommends the engineering and feasibility studies needed to develop a full proposal and technical design in approximately 5 years. In particular, the PAC agrees with the proponents that serious infrastructure questions must be addressed: identifying a suitable vertical shaft (or costing the construction of a new one), engineering km-long magnetic shielding to the level of nanotesla, vacuum to 10^{-4} Pa, and numerous additional considerations related to locating a 3MW research reactor on the surface at Homestake. Issues like safety, licensing, security, and backgrounds to other experiments need to be considered.

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)

Neutron source needed: small power 3.4 MW TRIGA reactor

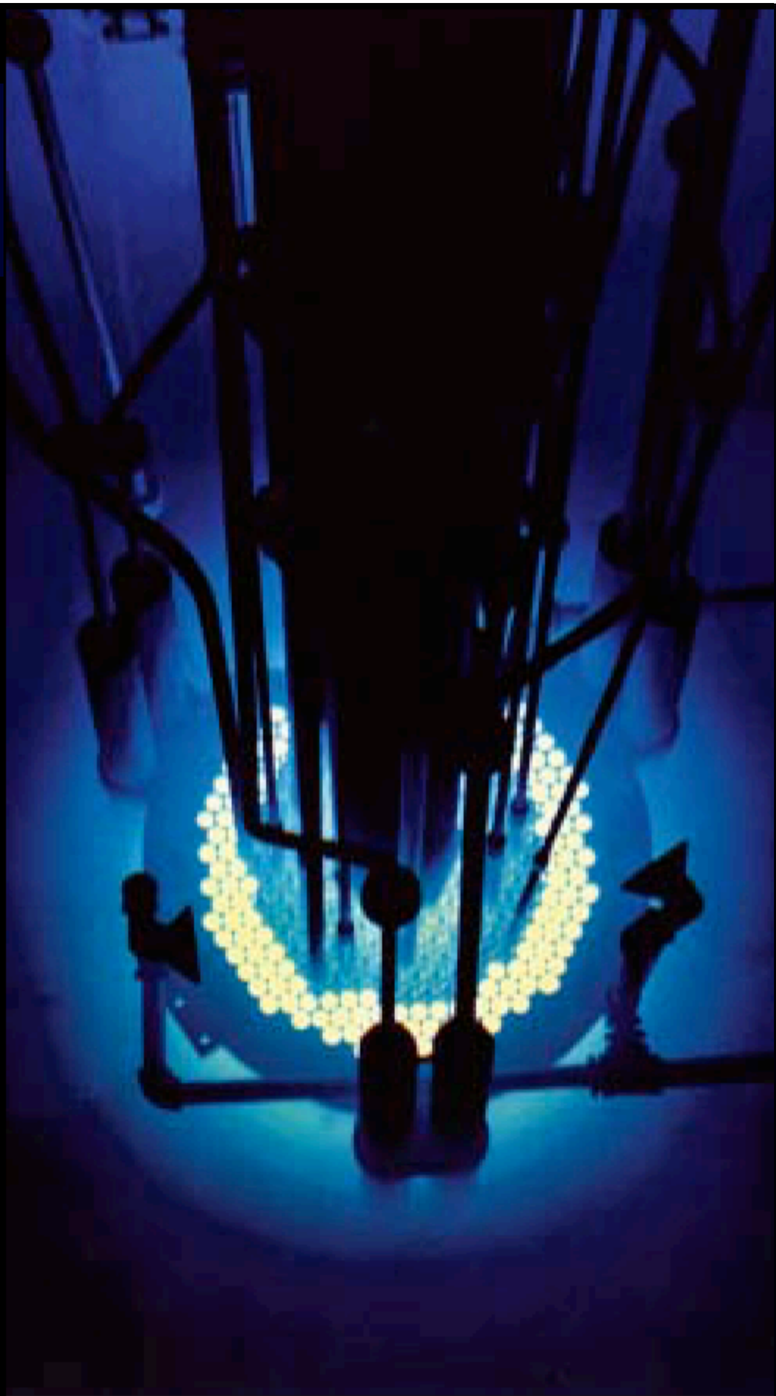


Fig. 17. Dry central cavity in annular core

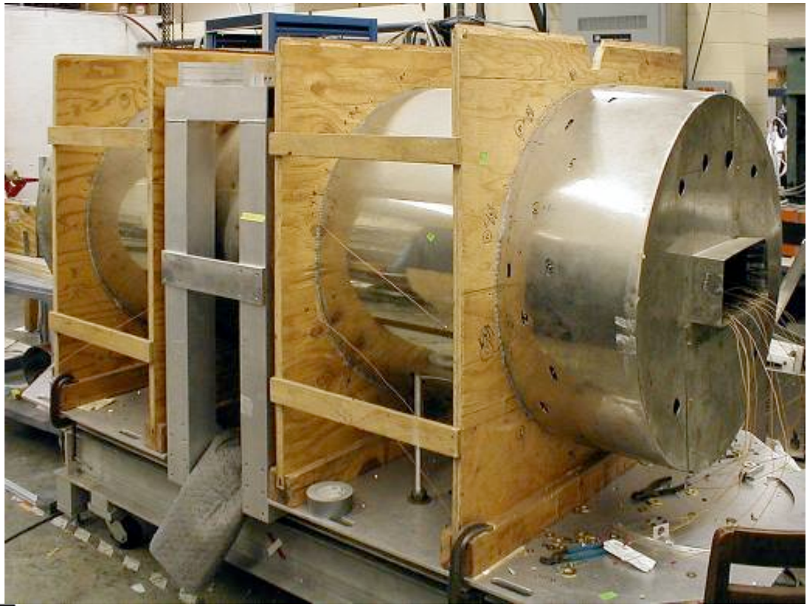
TRIGA Reactor picture courtesy of General Atomics

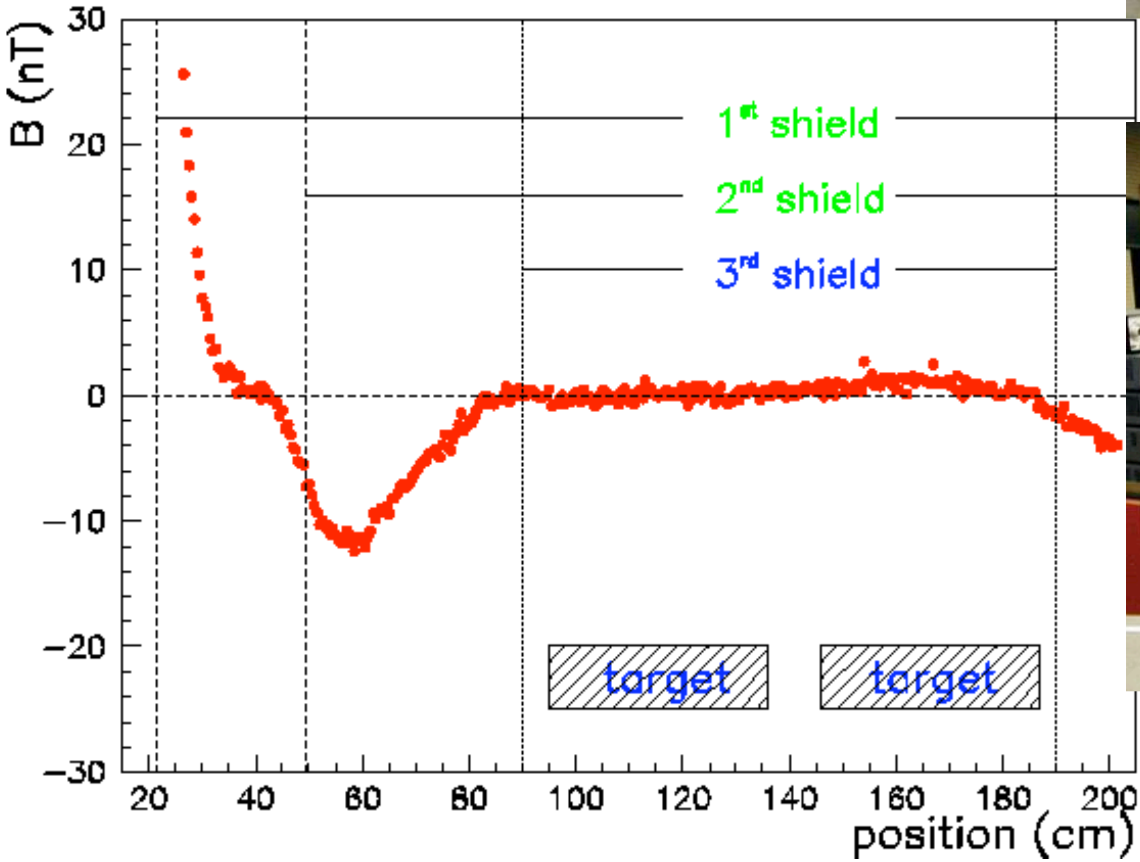
Vertical Cold Neutron Source (PNPI)

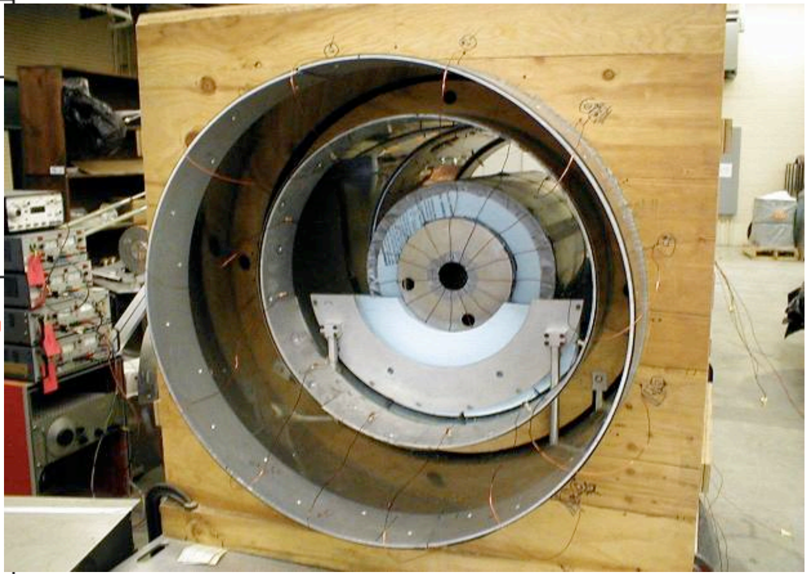
Delivered to new Australian research reactor, 18 MW power

Magnetic Shielding for n-4He Parity-odd Neutron Spin Rotation Experiment.
B~1nT using 3 passive shields

ILL experiment achieved sufficient shielding over 1m diameter, 100 m beam

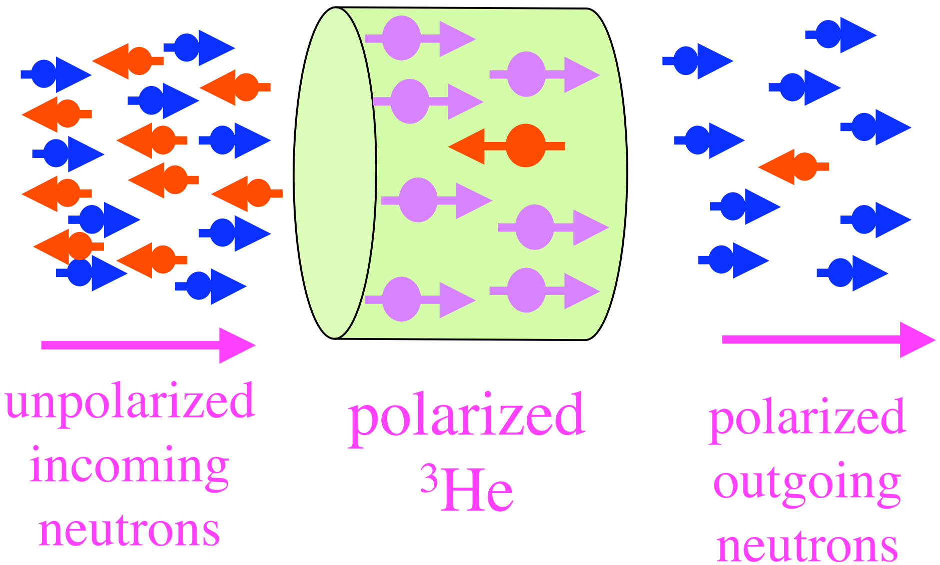


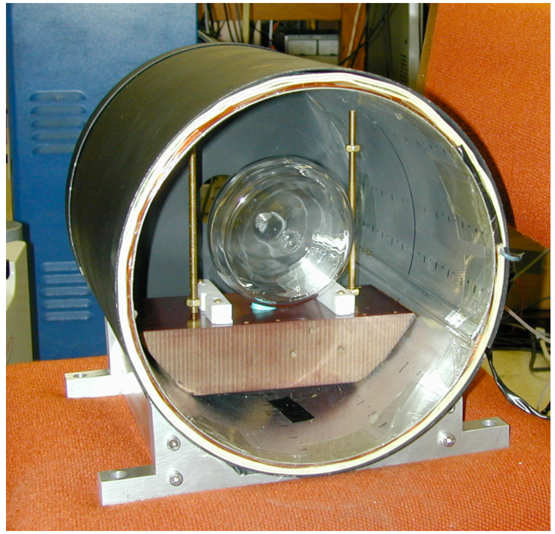




POLARIZED ^{3}He for Neutron Polarimetry

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

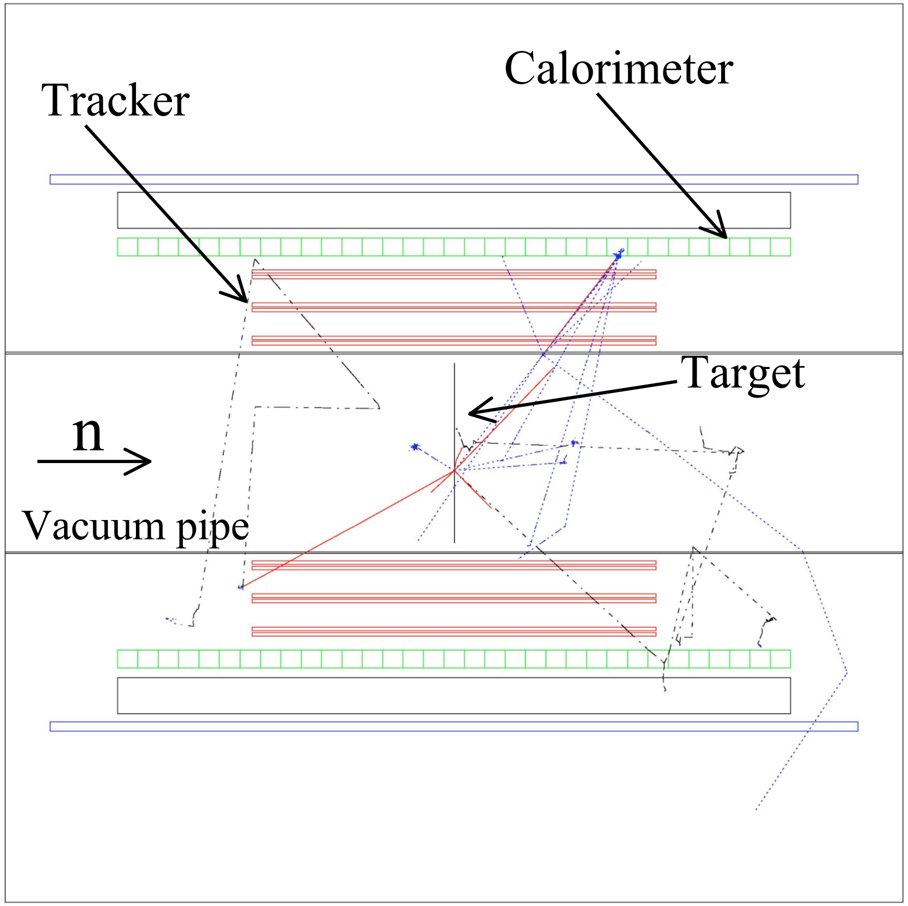
Polarizer/analyzer pair can measure B using neutron spin rotation

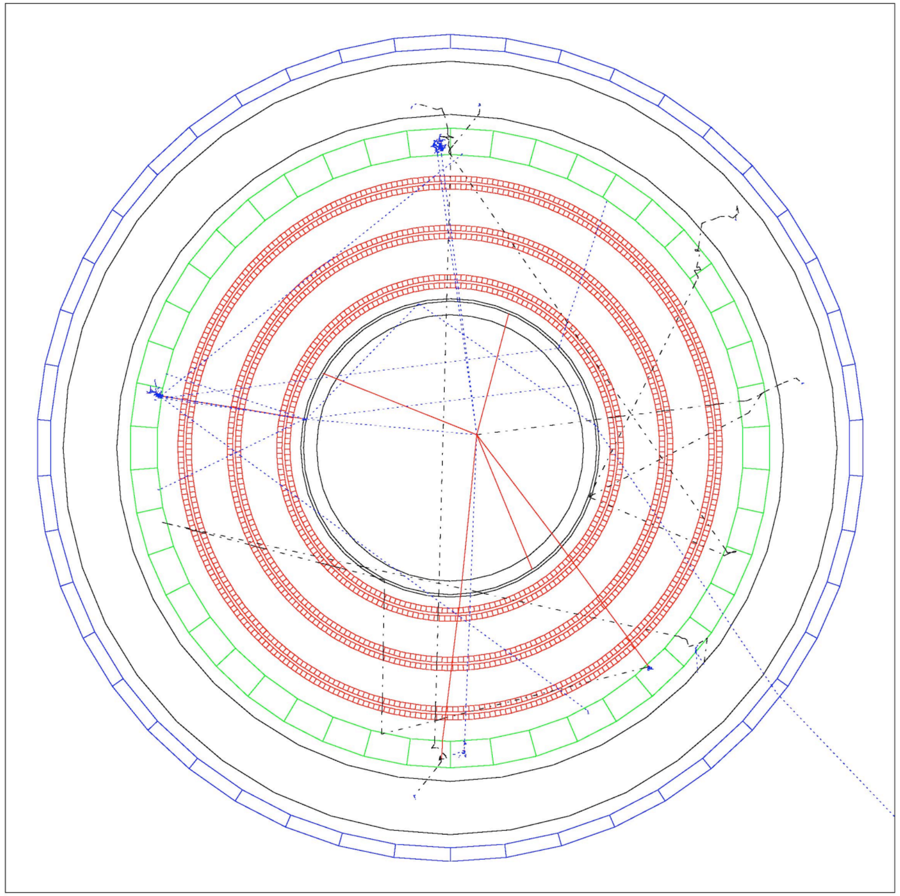
NIST, Indiana, Hamilton, Wisconsin

NSF CAREER→DEFG0203ER46093

Typical detector for "ILL type experiment"

Task is to reconstruct vertex, total energy (1.8 GeV), total momentum (0 GeV)

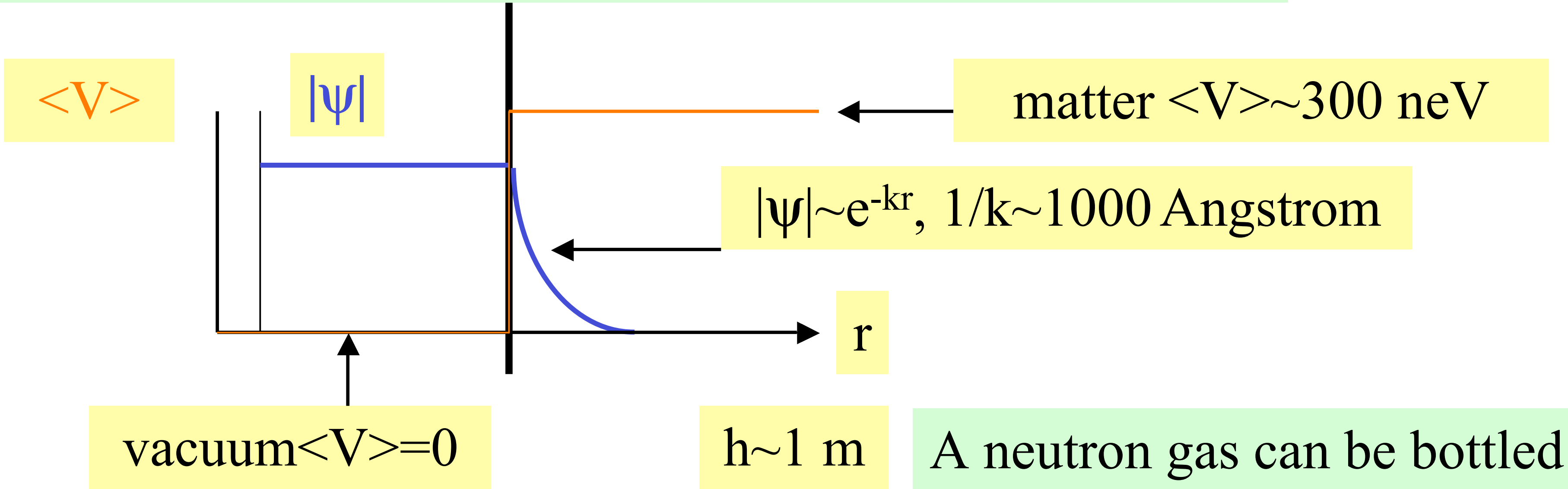


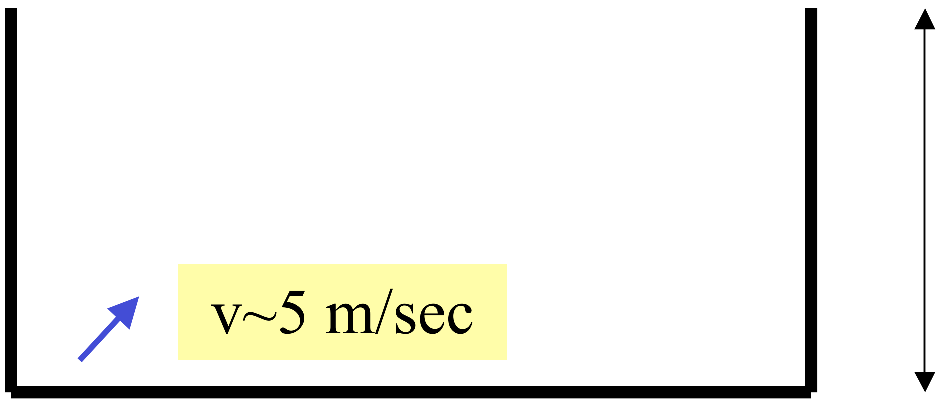


Three protons, two charged pions, and two neutral pions.

“Ultracold” Neutrons (UCN)

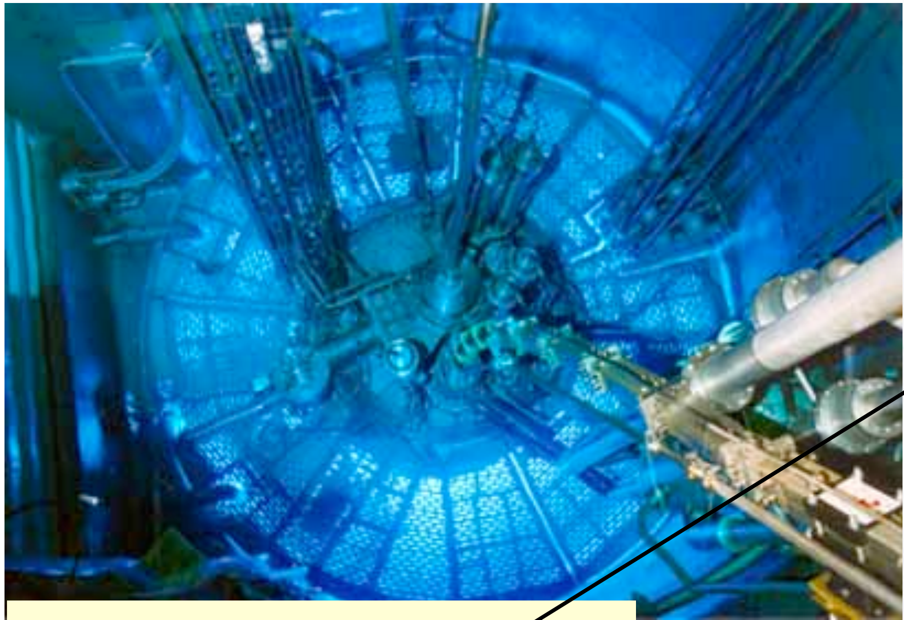
For very low energies (E_k-<V> negative, <V>~300 neV), matter forms a potential barrier for neutrons.





A neutron gas can be bottled (ρ~100/cc) using total external reflection. Due to gravity the bottle does not need a lid on top. Also B gradients can be used.

The ILL reactor UCN Turbine



UCN Neutron turbine

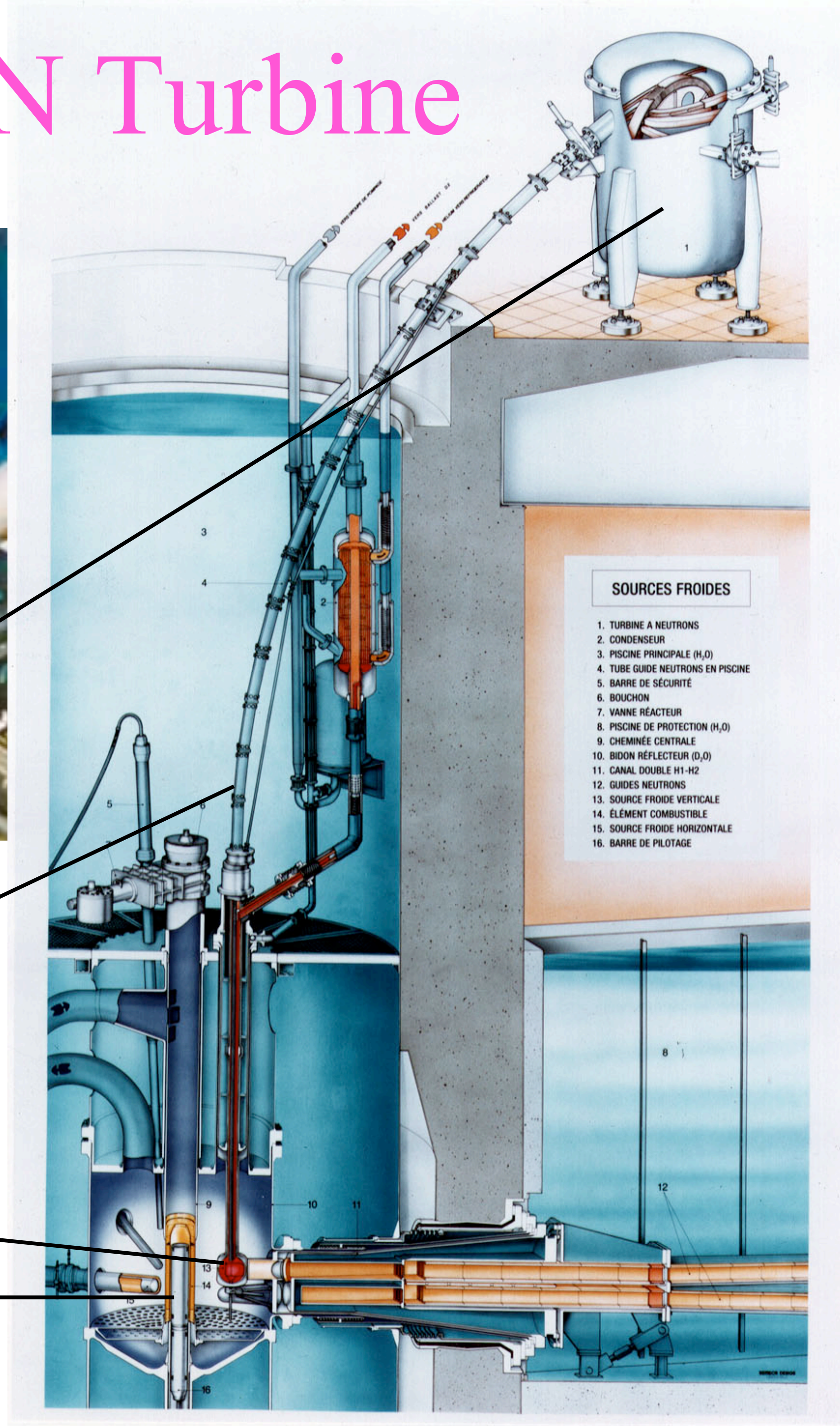
A. Steyerl (TUM - 1986)

Vertical guide tube

Cold source

Reactor core

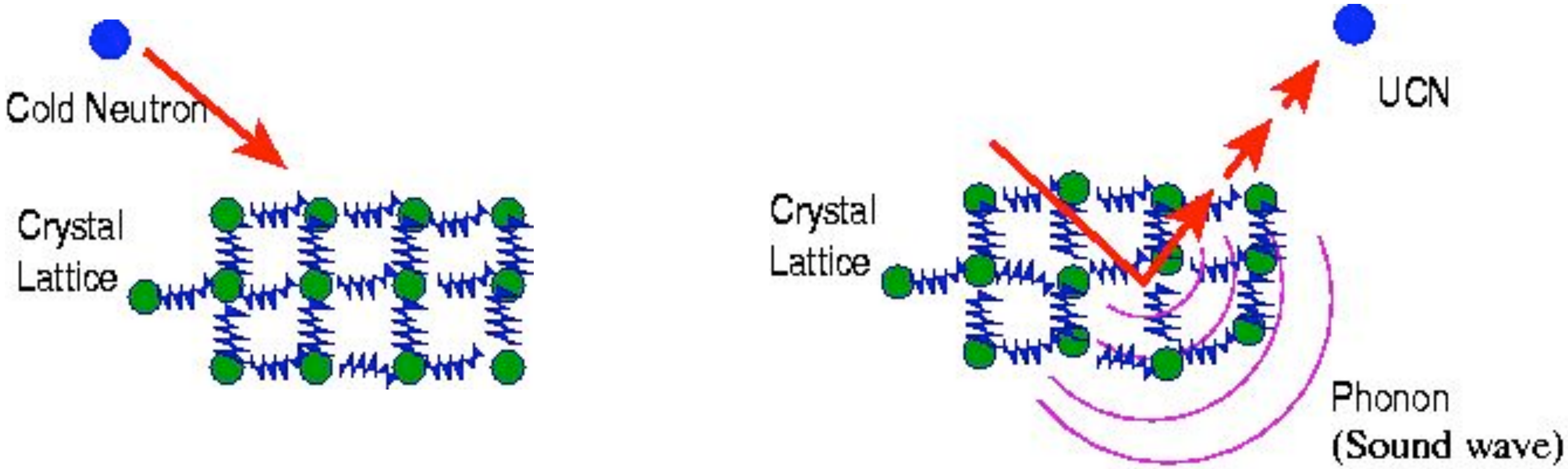
Density~50 neutrons/cc



"Superthermal" Process for Making UCN

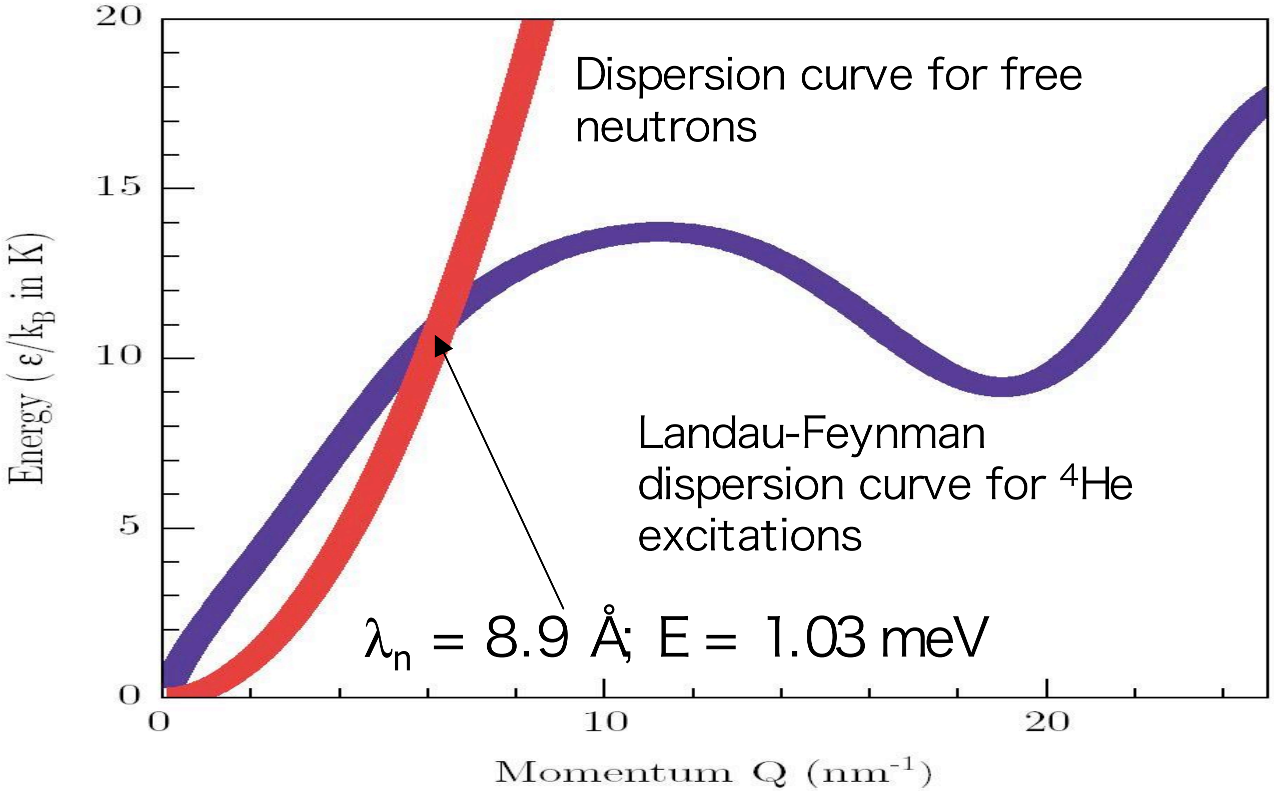
R. Golub and J. M. Pendlebury, Phys. Lett, A**53**, 133 (1975)

- Cold neutrons lose almost all their energy in one collision, becoming UCN.



- Rate of UCN energy gain is suppressed by cooling the moderator to low temperatures.
- Dissipative process->neutron phase space density is increased

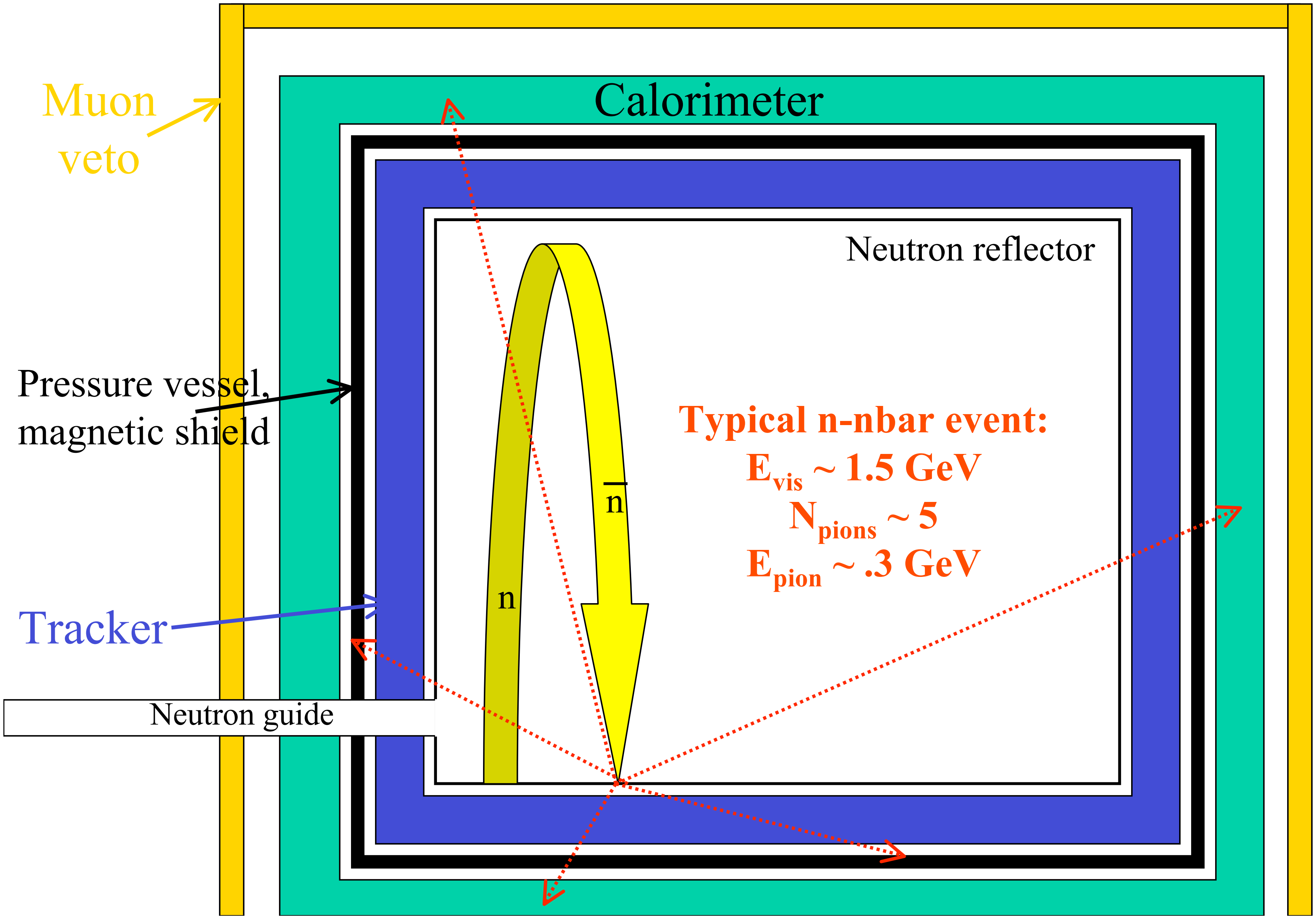
Example: UCN production in helium



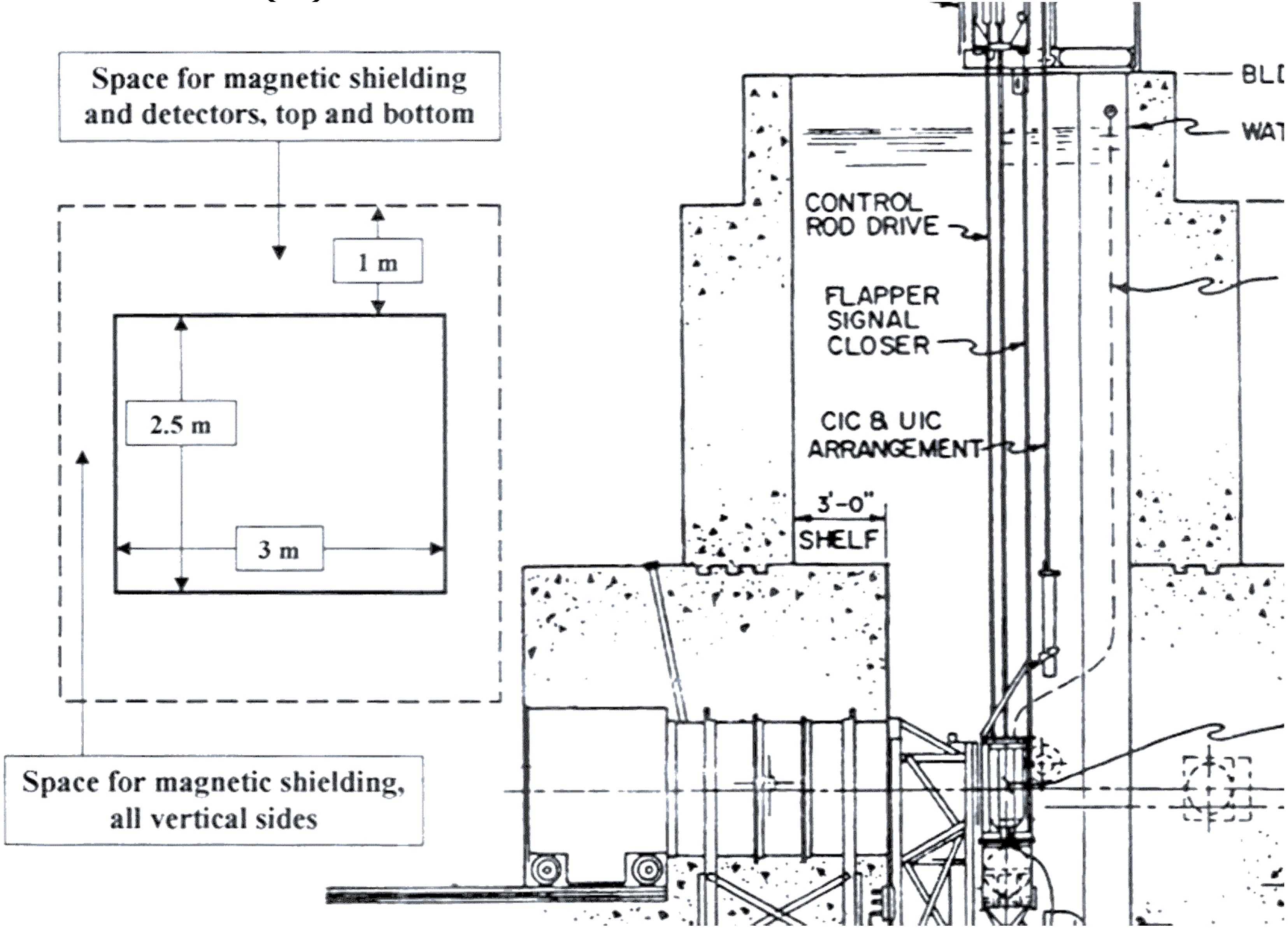
R. Golub and J.M. Pendlebury
Phys. Lett. **53A** (1975),
Phys. Lett. **62A** (1977)

- 1.03 meV (11 K) neutrons downscatter by emission of phonon in liquid helium at 0.5 K
- Upscattering suppressed: Boltzmann factor $e^{-E/kT}$ is small if T<<11K

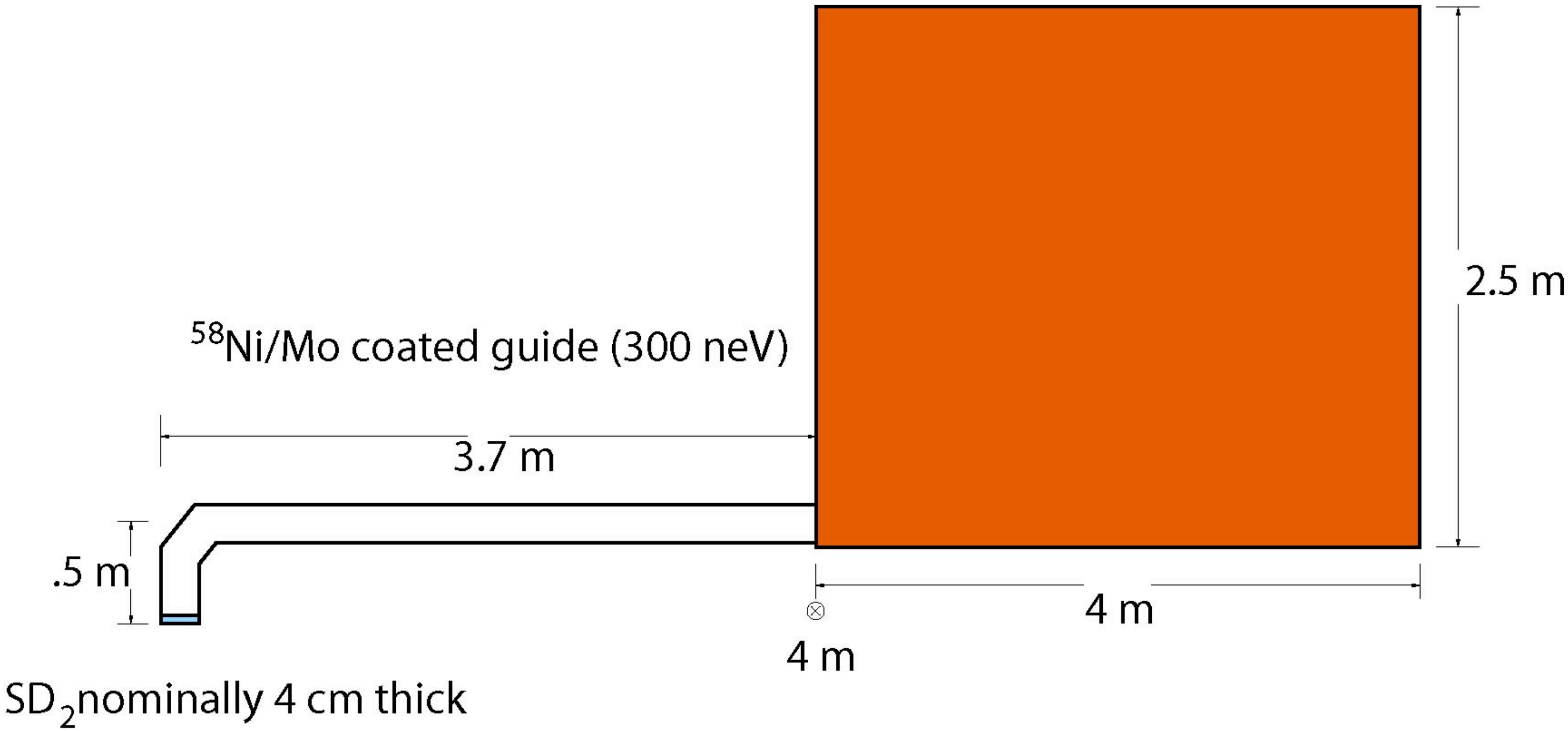
Possible apparatus for the "neutrons in the bottle" experiment



Possible UCN N-N Bar Experiment @PULSTAR/NC State



The geometry:



Preliminary results for base case (det eff = 1):

- A possible base case: NCState geometry, 4 cm thick SD2, 18 cm guides, .050s SD2 lifetime, a UCN energy cutoff of 430 neV initally

  Primary flux: 6.0×10^7 (below 305 neV)
  Box loading efficiency: 20 –32%
  Best case: diffuse walls, specular floor 3.5x10^9 discovery pot.
  325 s avg. residency

- Straightforward gains:

  Source thickness x2 (see Serebrov's geom): x 2
  Source lifetime → .075s +10%
  Running time: 4 years ("real")

  } $5.5 – 7 \times 10^9$

- Speculative gains:
  Multiphonon: x1.5(?)
  Coherent amplification: x2 (?)
  Solid Oxygen: x5 (?)

Various diffuse regions, wall potentials, same "best" case as above

Possible Future UCN Sources (M. Snow, from NNbar Workshop 2002)

source	moderator type	density (UCN/cc)	mode	fill rate (UCN/s)	timing
PSI	D2	1E+3	3s/600s	1E+7	>2006
Munich	D2	7E+4	CW	<3E+7	>2006
LANL	D2	2E+2	1s/10s	2E+5	2003
NSCU	D2	2E+3	CW	1E+7	>2005
KEK	4He	2E+5	CW	5E+7	>2008

Under development for other experiments (neutron EDM, neutron decay, neutron gravity tests,…)

NNbar search could be attractive possibility for future UCN facility

$n \rightarrow \bar{n}$ 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)	× 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 (6×10^{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 physics beyond the SM can be discovered by NNbar Oscillation Search

If discovered:

B violation, strong hint for direction of new physics beyond SM

may help to provide understanding of matter-antimatter asymmetry

If NOT discovered:

in combination with new nucleon decay experiments, can help set a new limit on the stability of matter

Search for Baryon and Lepton Number Violations Workshop
Sept. 20-22, 2007, LBL
http://inpa.lbl.gov/blnv/blnv.htm

EW SM sphaleron transition and violation of (B-L)
role of (B-L) violation in baryogenesis and cosmology
role of (B-L) violation in models of leptogenesis
relation of (B-L) with Left-Right Symmetry violation
violation of global quantum numbers in extra-dimensional models
status of (B-L) violation in proton decay search and models
review of proposed PDK search experiments for (B-L) violation
(B-L) violating nucleon decays (n-->3nu, others)
n-nbar oscillations models and expectations for oscillation time
n-nbar future experimental plans
Majorana neutrino searches and neutrinoless double beta decay
sterile neutrinos
mirror matter search (n --> n')
search for tau decays with (B-L) violation
search for (B-L) violation in hyperon decays
search for mirror matter at LHC and ILC
searches of B, L, and B-L violation at LHC and ILC

Conclusions

B is probably not conserved

Nucleon decay and n-nbar oscillations complementary ways to search for B violation. Many theories predict one or the other but not both

Can improve limits on $\Delta B=2$ from nucleon decay detectors by ~X5, atmospheric neutrinos already producing background, free neutron n-nbar oscillation search can possess much lower backgrounds

Free neutron searches for n-nbar transition probability can be improved 2-3 orders of magnitude, require either UCN or access to cold n source

Discovery would be very important, no discovery still helps set new limit on stability of matter

<u>B-L Workshop: Sept. 20-22, 2007, LBL/Berkeley</u>

Observable N-$\bar{N}$ Oscillation in High Scale Seesaw Models

Bhaskar Dutta,[1] Yukihiro Mimura,[1] and R. N. Mohapatra[2]

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[2]*Department of Physics and Center for String and Particle Theory, University of Maryland, College Park, Maryland 20742, USA*

(Received 26 October 2005; published 14 February 2006)

We discuss a realistic high scale ($v_{B-L} \sim 10^{12}$ GeV) supersymmetric seesaw model based on the gauge group $SU(2)_L \times SU(2)_R \times SU(4)_c$ where neutron-antineutron oscillation can be in the observable range. This is contrary to the naive dimensional arguments which say that $\tau_{N\text{-}\bar{N}} \propto v_{B-L}^5$ and should therefore be unobservable for seesaw scale $v_{B-L} \geq 10^5$ GeV. Two reasons for this enhancement are (i) accidental symmetries which keep some of the diquark Higgs masses at the weak scale and (ii) a new supersymmetric contribution from a lower dimensional operator. The net result is that $\tau_{N\text{-}\bar{N}} \propto v_{B-L}^2 v_{\rm wk}^3$ rather than v_{B-L}^5. The model also can explain the origin of matter via the leptogenesis mechanism and predicts light diquark states which can be produced at LHC.

In the Supersymmetric Pati-Salam type model violation of local (B–L) symmetry with $\Delta L=2$ gives masses to heavy right-handed neutrinos generating regular neutrino masses via seesaw mechanism. Same mechanism with $\Delta B=2$ determines the operator for N-Nbar transition. This operator was shown to have very weak power dependence on the seesaw scale, i.e. $1/M^2_{seesaw}$ rather than $1/M^5_{seesaw}$ as in naive dimensional arguments. That makes N-Nbar observable within the reach of present experimental techniques. The model also predicts light diquark states that can be produced at LHC.

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–$\overline{N}$ oscillation time in these models, $\tau_{N-\overline{N}} \leqslant 10^9$–$10^{10}$ s. This suggests that a modest improvement in the current limit on $\tau_{N-\overline{N}}$ of 0.86×10^8 s will either lead to the discovery of N–$\overline{N}$ oscillations, or will considerably restrict the allowed parameter space of an interesting class of neutrino mass models.

For wide class of L-R and super-symmetric models predicted
n-nbar upper limit is within a reach of new n-nbar search experiments!
If not seen, n-nbar should restrict a wide class of SUSY models.

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Post–Sphaleron Baryogenesis

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Abstract

We present a new mechanism for generating the baryon asymmetry of the universe directly in the decay of a singlet scalar field S_r with a weak scale mass and a high dimensional baryon number violating coupling. Unlike most currently popular models, this mechanism, which becomes effective after the electroweak phase transition, does not rely on the sphalerons for inducing a nonzero baryon number. CP asymmetry in S_r decay arises through loop diagrams involving the exchange of $W^{\pm}$ gauge bosons, and is suppressed by light quark masses, leading naturally to a value of $\eta_B \sim 10^{-10}$. We show that the simplest realization of this mechanism, which uses a six quark $\Delta B = 2$ operator, predicts colored scalars accessible to the LHC, and neutron–antineutron oscillation within reach of the next generation experiments.

New baryogenesis models with mechanisms that are experimentally testable

Baryon asymmetry of universe is generated at the temperatures below E-W transitions via new color scalars with masses 0.1-1 TeV that might be observable at LHC and lead to the neutron-antineutron oscillations within reach of the next generation experiments.

New baryogenesis models with mechanisms that are experimentally testable

Baryogenesis by R-parity violating top quark decays and neutron-antineutron oscillations

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Abstract

Generation of the cosmological baryon asymmetry in SUSY based model with broken R-parity and low scale gravity is considered. The model allows for a long-life time or even stable proton and observable neutron-antineutron oscillations.

Generation of the cosmological baryon asymmetry in SUSY based model with broken R-parity and low scale gravity is considered. The model allows for a long-life time or even stable proton and observable neutron-antineutron oscillations.

Low quantum gravity scale models

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Proton decay is strongly suppressed in this model, but n-nbar should occur since n_R has no gauge charges

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

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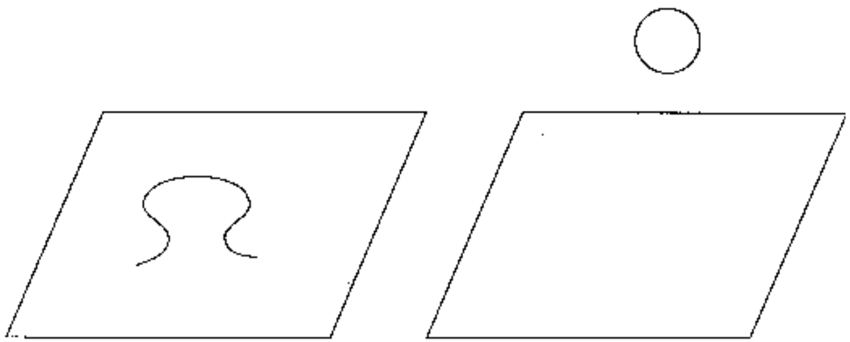

Fig. 1. Creation of baby branes.

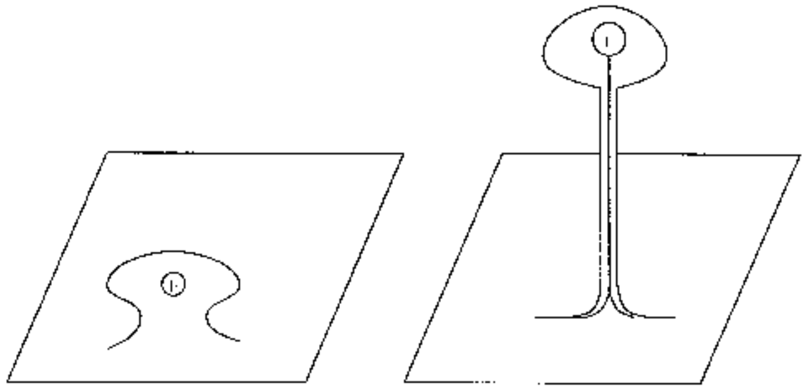

Fig. 2. Flux tube holding the baby brane with a local charge.

Low quantum gravity scale models

In this model where global charges are violated by Black Holes the rates for proton-decay, neutron-antineutron oscillations, and lepton-violating rare decays are suppressed to below experimental bounds even for large extra dimensions with TeV-scale gravity. Neutron-antineutron oscillations and anomalous decays of muons, τ-leptons, and K and B-mesons open a promising possibility to observe TeV gravity effects with a minor increase of existing experimental accuracy.

A Black Hole Conjecture and Rare Decays in Theories with Low Scale Gravity

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Abstract

In models with large extra dimensions, where the fundamental gravity scale can be in the electroweak range, gravitational effects in particle physics may be noticeable even at relatively low energies. In this paper, we perform simple estimates of the decays of elementary particles with a black hole intermediate state. Since black holes are believed to violate global symmetries, particle decays can violate lepton and baryon numbers. Whereas previous literature has claimed incompatibility between these rates (e.g. p-decay) and existing experimental bounds, we find suppressed baryon and lepton-violating rates due to a new conjecture about the nature of the virtual black holes. We assume here that black holes lighter than the (effective) Planck mass must have zero electric and color charge and zero angular momentum – this statement is true in classical general relativity and we make the conjecture that it holds in quantum gravity as well. If true, the rates for proton-decay, neutron-antineutron oscillations, and lepton-violating rare decays are suppressed to below experimental bounds even for large extra dimensions with TeV-scale gravity. Neutron-antineutron oscillations and anomalous decays of muons, τ-leptons, and K and B-mesons open a promising possibility to observe TeV gravity effects with a minor increase of existing experimental accuracy.

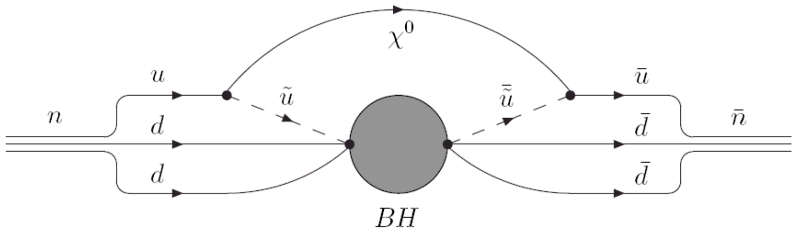

Figure 5: $(n - \bar{n})$-oscillation with supersymmetric particles. In this case the observation of the phenomenon may be accessible to future experiments.

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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Quarks and leptons belong to different branes separated by an extra-dimension; proton decay is strongly suppressed, n-nbar is NOT since quarks and anti-quarks belong to the same brane.

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Gravitational Baryogenesis

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We show that a gravitational interaction between the derivative of the Ricci scalar curvature and the baryon-number current dynamically breaks *CPT* in an expanding Universe and, combined with baryon-number-violating interactions, can drive the Universe towards an equilibrium baryon asymmetry that is observationally acceptable.

Effective D = 7 operators can generate n-nbar transitions in such model.