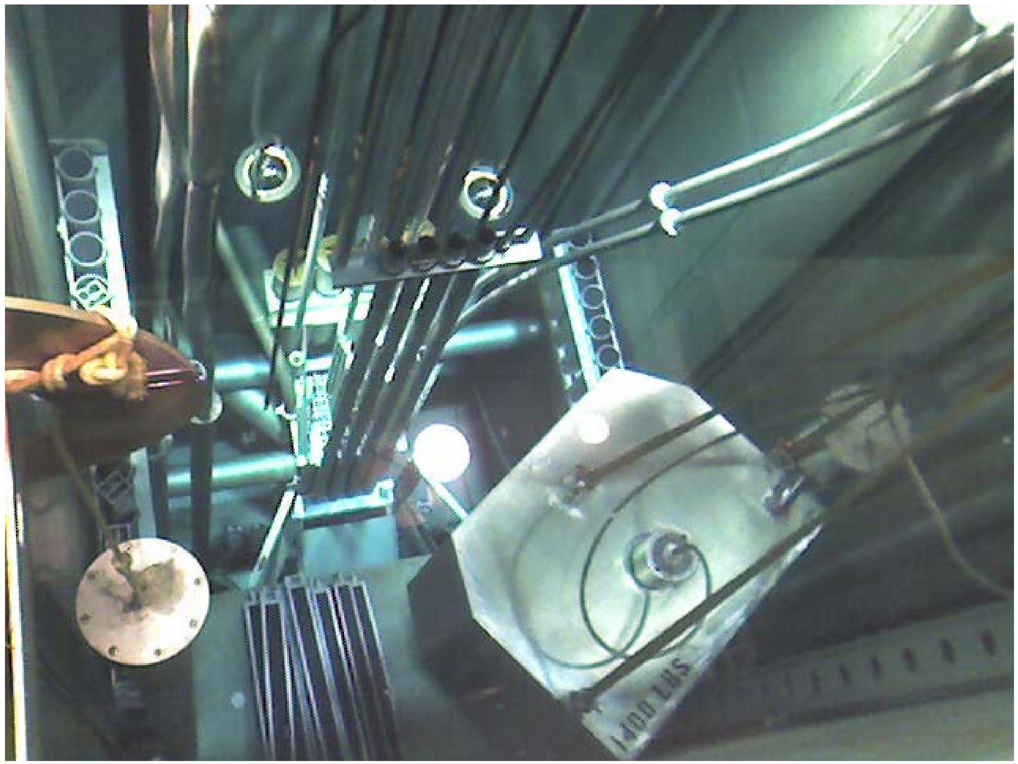
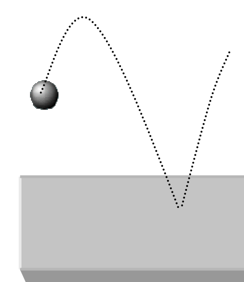
Improved Experimental Searches for Neutron-Antineutron Oscillations





A.R.Young
NCState University

Outline

- Motivate neutron-antineutron (N-Nbar) oscillations experiments
- Describe the ILL experiment defining best limit for free neutrons
- Outline an improved search for N-Nbar oscillations using a vertical geometry with cold neutrons
- A second alternative: ultracold neutrons
- Summary and Conclusions: a staged approach

Some Current Big Questions in Physics

- What is the source of the baryon-antibaryon asymmetry in the universe?
- Where does neutrino mass come from?
- Is nuclear matter stable?
- Do we live on branes?

All Directly linked to potentially **observable** neutron-antineutron oscillations in a next generation experiment!

$n \leftrightarrow \bar{n}$ The Idea's "Been Around…" $|\Delta B|=2$; $|\Delta(B-L)|=2$

- There are no laws of nature that would forbid the N ↔ Nbar transitions except the conservation of "*baryon charge (number)*":

M. Gell-Mann and A. Pais, Phys. Rev. 97 (1955) 1387
L. Okun, Weak Interaction of Elementary Particles, Moscow, 1963

- N ↔ Nbar was first suggested as a possible mechanism for explanation of Baryon Asymmetry of Universe *by V. Kuzmin, 1970*

- N ↔ Nbar works within GUT + SUSY ideas. First considered and developed within the framework of L-R symmetric Unification models

by R. Mohapatra and R. Marshak, 1979 …

- Fast anomalous SM interactions (*sphalerons*) in early Universe at TeV scales require that (B–L) should be violated *V. Kuzmin, V. Rubakov, M. Shaposhnikov, 1985*

Recent $n \leftrightarrow \bar{n}$ theoretical developments $|\Delta B|=2$; $|\Delta(B-L)|=2$

- 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 and large extra dimensions

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 scales

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

Activity continues! Ex: this summer Frampton developed an instanton model that can produce N-Nbar oscillations (without proton decay) at current experimental limits

18 October 2001

PHYSICS LETTERS B

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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Received 12 August 2001; accepted 27 August 2001
Editor: M. Cvetič

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.

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

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(Received 26 October 2005; published 14 February 2006)

We discuss a realistic high scale ($v_{B\text{-}L} \sim 10^{12}$ 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 $\tau_{N\text{-}\bar{N}} \propto v_{B\text{-}L}^5$ and should therefore be unobservable for seesaw scale $v_{B\text{-}L} \geq 10^5$ 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 $\tau_{N\text{-}\bar{N}} \propto v_{B\text{-}L}^2 v_{\rm wk}^3$ rather than $v_{B\text{-}L}^5$. 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. $1/M^2_{\rm seesaw}$ rather than $1/M^5_{\rm seesaw}$ 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 and the origin of matter via leptogenesis

Low energy scale quantum gravity models

ELSEVIER

5 August 1999

Physics Letters B 460 (1999) 47–57

PHYSICS LETTERS B

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

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

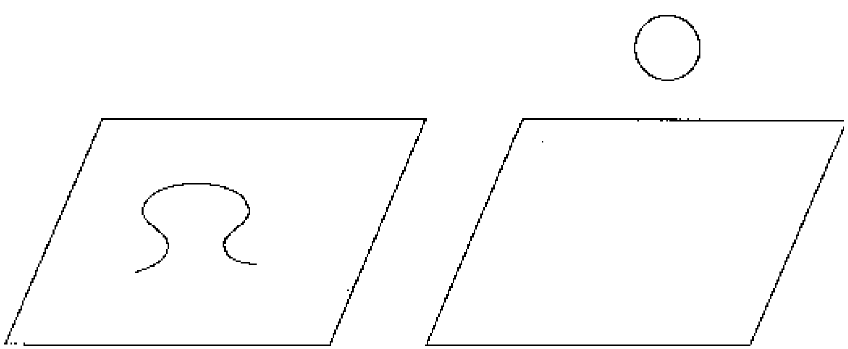

Fig. 1. Creation of baby branes.

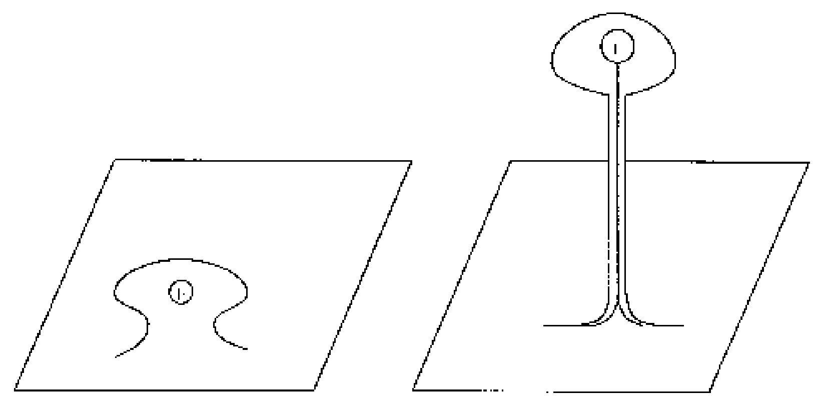

Fig. 2. Flux tube holding the baby brane with a local charge.

VOLUME 88, NUMBER 17 PHYSICAL REVIEW LETTERS 29 APRIL 2002

n-$\bar{n}$ Oscillations in Models with Large Extra Dimensions

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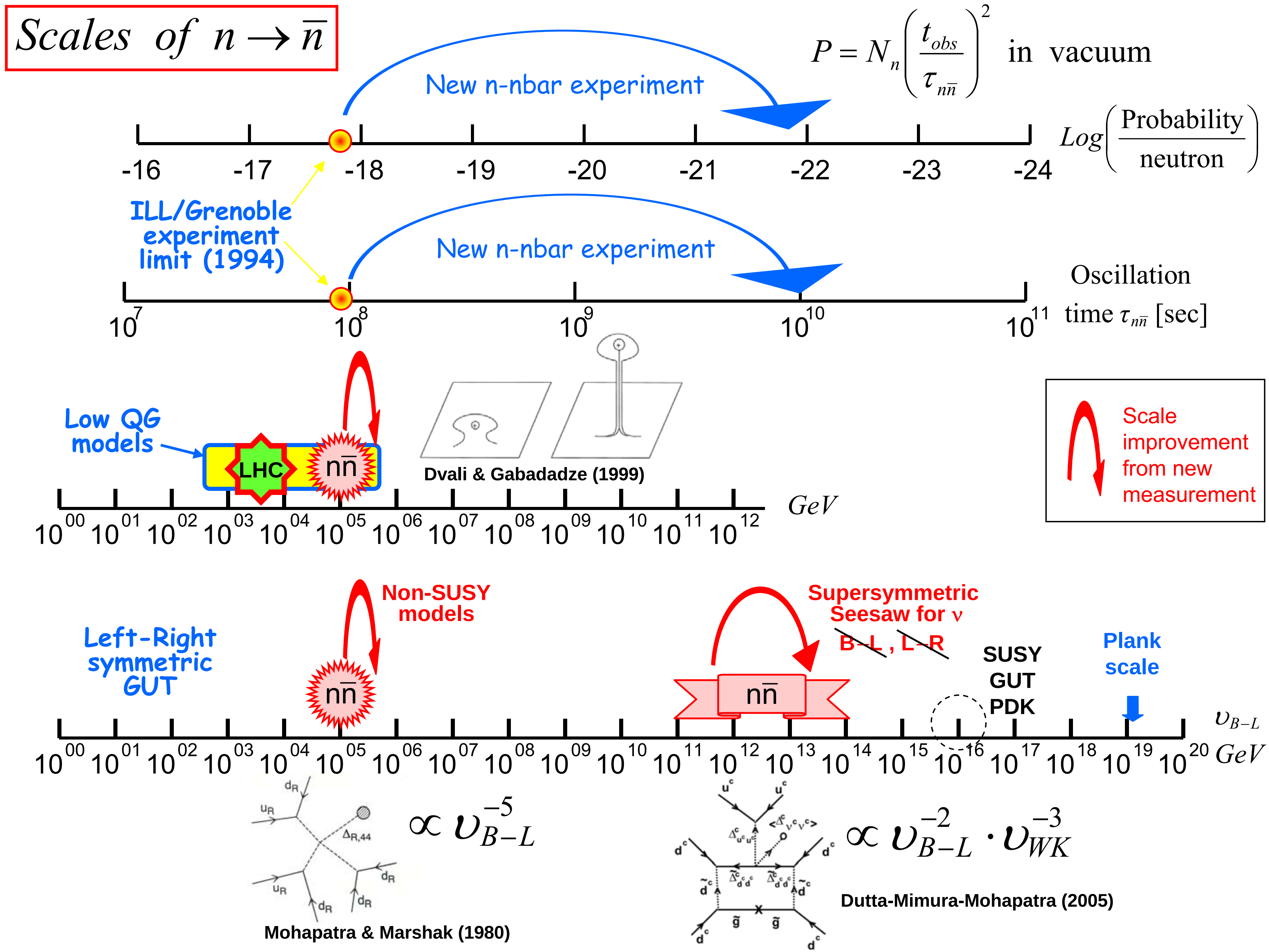
(Received 27 December 2001; published 12 April 2002)

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.

DOI: 10.1103/PhysRevLett.88.171601 PACS numbers: 11.10.Kk, 11.30.Fs, 14.20.Dh

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.



Scales of $n \rightarrow \bar{n}$
$P = N_n \left(\frac{t_{obs}}{\tau_{n\bar{n}}} \right)^2$ in vacuum
New n-nbar experiment
-16 -17 -18 -19 -20 -21 -22 -23 -24
$Log\left(\frac{\text{Probability}}{\text{neutron}}\right)$
ILL/Grenoble experiment limit (1994)
New n-nbar experiment
Oscillation time $\tau_{n\bar{n}}$ [sec]
10^7 10^8 10^9 10^{10} 10^{11}
Low QG models
LHC
$n\bar{n}$
Dvali & Gabadadze (1999)
GeV
10^{00} 10^{01} 10^{02} 10^{03} 10^{04} 10^{05} 10^{06} 10^{07} 10^{08} 10^{09} 10^{10} 10^{11} 10^{12}
Scale improvement from new measurement
Non-SUSY models
Left-Right symmetric GUT
$n\bar{n}$
Supersymmetric Seesaw for ν
~~B-L~~, ~~L-R~~
$n\bar{n}$
SUSY GUT PDK
Plank scale
υ_{B-L}
10^{00} 10^{01} 10^{02} 10^{03} 10^{04} 10^{05} 10^{06} 10^{07} 10^{08} 10^{09} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20} GeV
$\propto \upsilon_{B-L}^{-5}$
Mohapatra & Marshak (1980)
$\propto \upsilon_{B-L}^{-2} \cdot \upsilon_{WK}^{-3}$
Dutta-Mimura-Mohapatra (2005)

Proton Decay vs. $N\bar{N}$

P-decay seems to explore higher mass scales, but…

- Both ΔB=1, P-decay and N-Nbar can be incorporated into can be incorporated into models (SO(10) and supersymmetric Pati-Salaam) which explain generic problems of neutrino mass, dark matter, baryogenesis – essentially complimentary physics
- For P decay, only practical search underground but neutrino backgrounds increasingly problematic – don't go away with increasing detector mass (also a factor in underground NN-bar searches)!
- Free N-Nbar limits for nuclear matter stability can exceed those of even next generation P-decay
- Incredible prospect of testing the systematic validity of the result by "switching off" NN-bar oscillations with magnetic field while leaving entire experiment essentially unchanged!

Experimental NN-bar Searches

- Nucleon decay (bound N oscillates to N-bar and annihilates on other nucleons)
- Free N-Nbar oscillations in beams of cold neutrons

Given huge number of atoms available in large scale underground nucleon decay experiments, seems likely to provide best limits…

Neutron-Antineutron transition probability: **quasifree** condition

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 $\alpha \le 10^{-23} eV$

$$\tau_{n\bar{n}} = \hbar/\alpha$$

Contributions to V:

<Vmatter>~100 neV, proportional to 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

Some $|\Delta(B-L)|=2$ nucleon decay modes (PDG'06+) from large scale, underground experiments

(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

- In the presence of physics background new limits $\sim \sqrt{kt \times yr}$
- In the presence of background positive decay observation problematic

$$\tau_{bound} = R \cdot \tau^2_{free}$$

where $R \sim 10^{23}\ s^{-1}$

R is "nuclear suppression factor". Uncertainty of R from nuclear models is ~ factor of 2

PDG 2004:
Limits for both
free reactor neutrons and
neutrons bound inside nucleus

LIMIT ON $n\bar{n}$ OSCILLATIONS

Mean Time for $n\bar{n}$ Transition in Vacuum

A test of ΔB=2 baryon number nonconservation. MOHAPATRA 80 and MOHAPATRA 89 discuss the theoretical motivations for looking for $n\bar{n}$ oscillations. DOVER 83 and DOVER 85 give phenomenological analyses. The best limits come from looking for the decay of neutrons bound in nuclei. However, these analyses require model-dependent corrections for nuclear effects. See KABIR 83, DOVER 89, ALBERICO 91, and GAL 00 for discussions. Direct searches for $n \to \bar{n}$ transitions using reactor neutrons are cleaner but give somewhat poorer limits. We include limits for both free and bound neutrons in the Summary Table.

VALUE (s)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$>1.3 \times 10^8$	90	CHUNG	02B	SOU2	*n* bound in iron
$>8.6 \times 10^7$	90	BALDO-...	94	CNTR	Reactor (free) neutrons
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$>1 \times 10^7$	90	BALDO-...	90	CNTR	See BALDO-CEOLIN 94
$>1.2 \times 10^8$	90	BERGER	90	FREJ	*n* bound in iron
$>4.9 \times 10^5$	90	BRESSI	90	CNTR	Reactor neutrons
$>4.7 \times 10^5$	90	BRESSI	89	CNTR	See BRESSI 90
$>1.2 \times 10^8$	90	TAKITA	86	CNTR	*n* bound in oxygen
$>1 \times 10^6$	90	FIDECARO	85	CNTR	Reactor neutrons
$>8.8 \times 10^7$	90	PARK	85B	CNTR	
$>3 \times 10^7$		BATTISTONI	84	NUSX	
$> 2.7 \times 10^7 – 1.1 \times 10^8$		JONES	84	CNTR	
$>2 \times 10^7$		CHERRY	83	CNTR	

Bound n: J. Chung et al., (Soudan II)
Phys. Rev. D 66 (2002) 032004 $> 7.2 \cdot 10^{31}$ years

Free n: M. Baldo-Ceolin et al., (ILL/Grenoble) *Z. Phys* **C63** (1994) 409
with $P = (t/\tau_{free})^2$

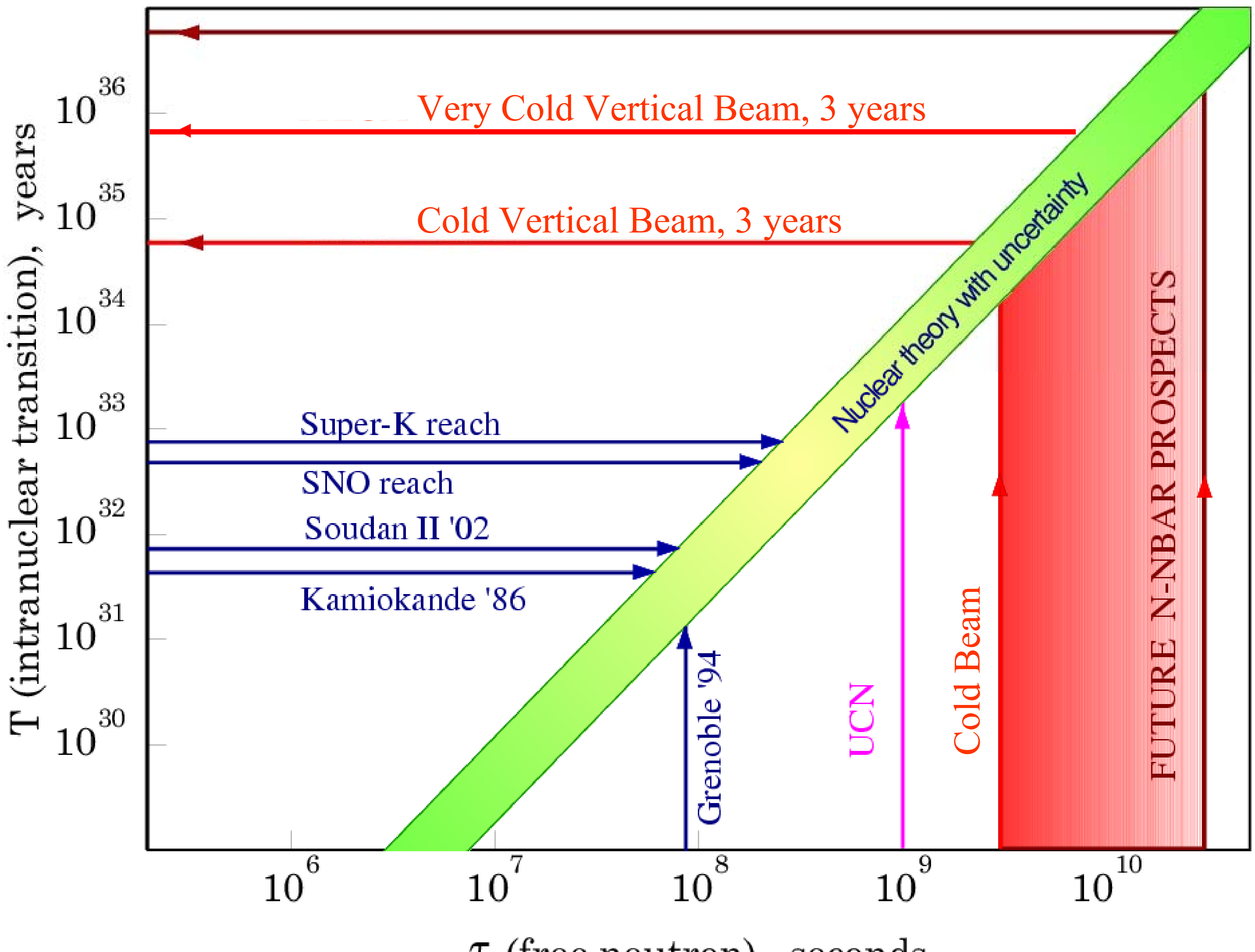
2007: SuperK: $\tau_{nn} > 2.7\text{x}10^8$ s

2010: SNO limits coming soon
Thesis work of Marc Bergevin, supervised by A. W. Poon, analyzed 1/3 of SNO data, just complete – atm ν's dominant backgrnd

Search with free neutrons is far more efficient than with bound neutrons

Stability of matter from Neutron-Antineutron transition search

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



High payoffs of improved searches for N-Nbar

Expected improvement if N-Nbar search sensitivity increased ~1,000!

<u>If discovered:</u>

- n→nbar will establish a new force of nature and a new phenomenon leading to the physics beyond the SM at the energy scale above TeV

- will help to provide understanding of matter-antimatter asymmetry and origin of neutrino mass

<u>If NOT discovered:</u>

- within the reach of improved experimental sensitivity will set a new limit on the stability of matter exceeding the sensitivity of X-large nucleon decay experiments
- will place constraints on large class of R-parity conserving supersymmetric models

Cold neutron beam experiments to measure N-Nbar oscillations

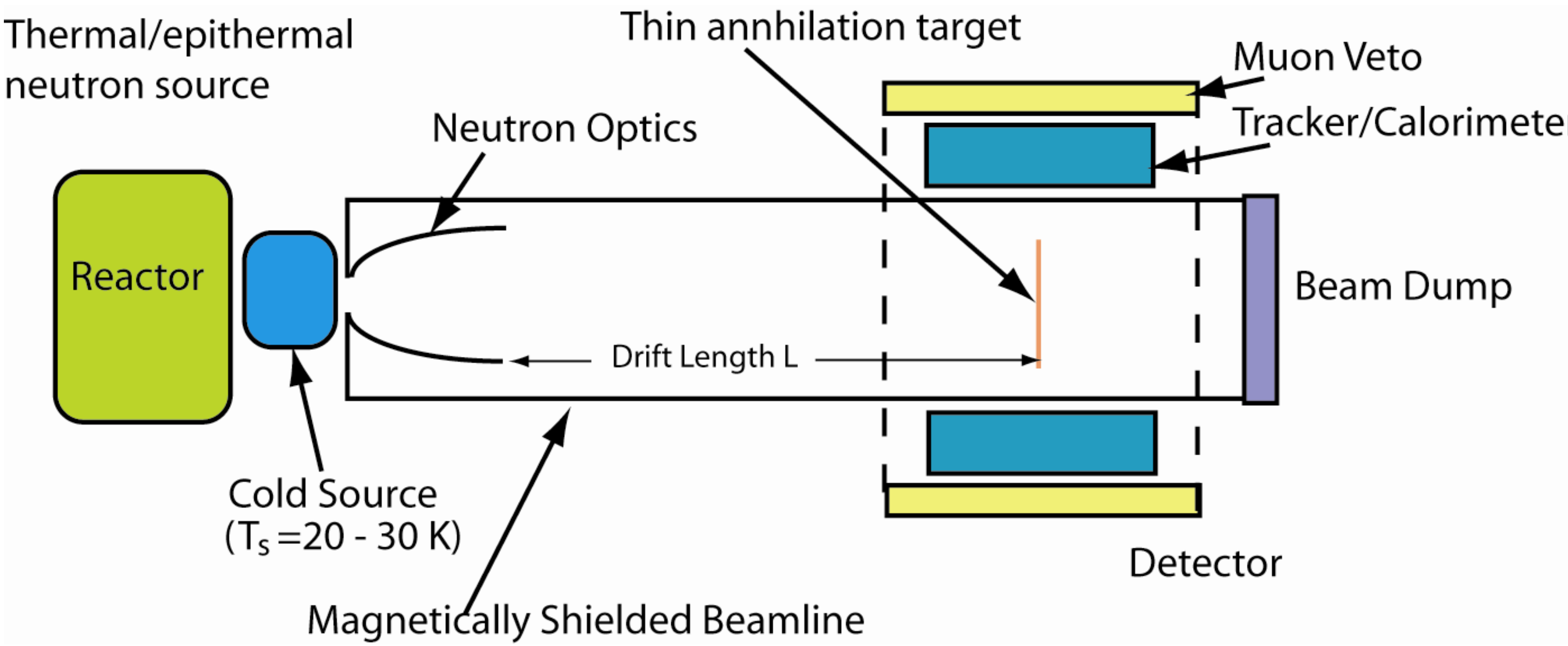


Figure of Merit: Nt^2

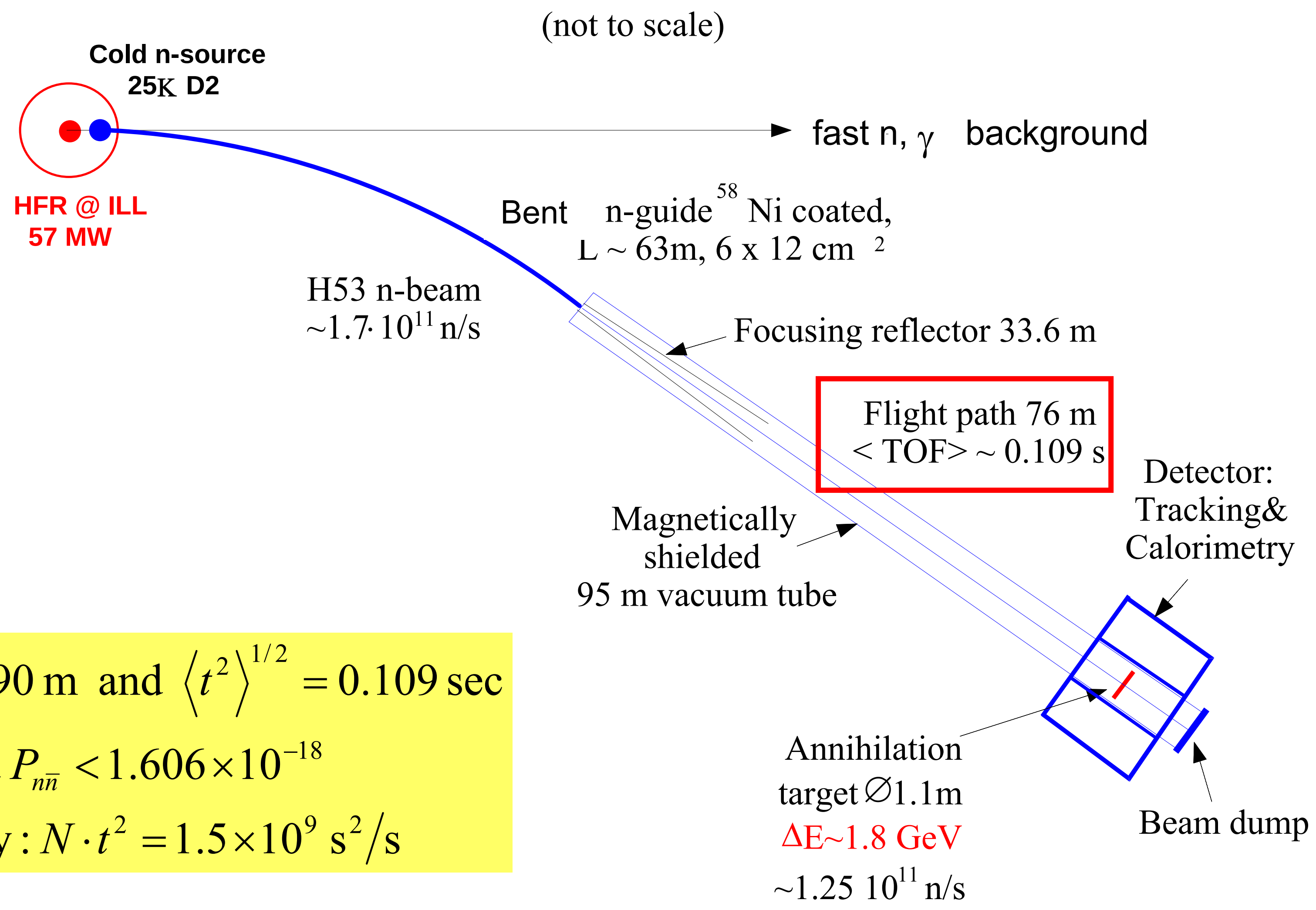
Experimental strategy:

Maximize drift length L
Minimize T_s
Maximize cold flux

Previous n-nbar search experiment with free neutrons

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

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



with $L \sim 90$ m and $\langle t^2 \rangle^{1/2} = 0.109$ sec

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

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

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

Reconstruct multi-pion events with limited streamer tubes and scintillator planes (dominant decay mode is 5 pion "star")

No background!

No candidates observed.

Measured limit for a year of running:

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

= 1 unit of sensitivity

Volume 236, number 1 PHYSICS LETTERS B 8 February 1990

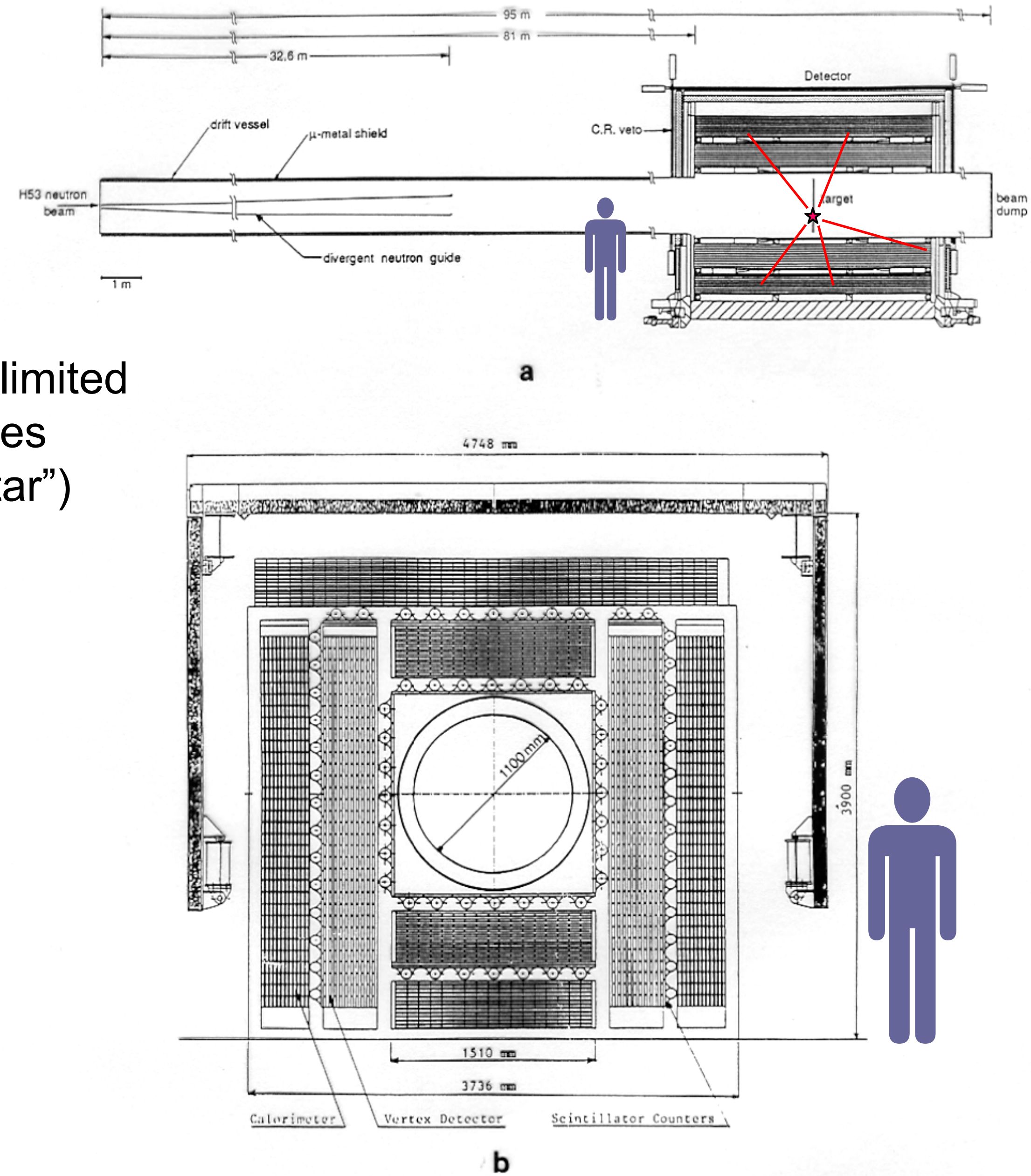


Fig. 1. (a) Experimental apparatus showing the "quasi free" neutron propagation length with the divergent guide, the target and the detection system. (b) Cross sectional view of the detector.

The "on –off" switch for phenomena at 10^{11} GeV

- When quasi-free condition is **violated**, *i.e.* when B > 10 nT in our geometry, oscillations not observable
- Background processes essentially unchanged
- Powerful test of systematic errors associated with a positive result!

Where to Go from Here?

Improve free neutron searches, we need to:

- Increase neutron flux
- Increase measurement interval

Solution:

Use reactor (similar to ILL) with improved neutron optics coupled very closely to source, to increase transmitted flux to more distant target

Problem:

No reactors currently available where appropriate, close-coupled concentrator optics can be mounted to long (300m or more) beamline

What Other Alternatives Are There?

Need an alternative source of neutrons and methods for enhancing sensitivity:

1. Low power cyclotron or TRIGA reactor coupled to cold source

+

2. Vertical layout: Earth's gravity provides "focusing" , permits much weaker neutron source
(about 100 kW should be adequate, scaling from PSI SINQ source at 570 MeV)

HOMESTAKE DUSEL

Deep Underground Science and Engineering Laboratory

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

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]

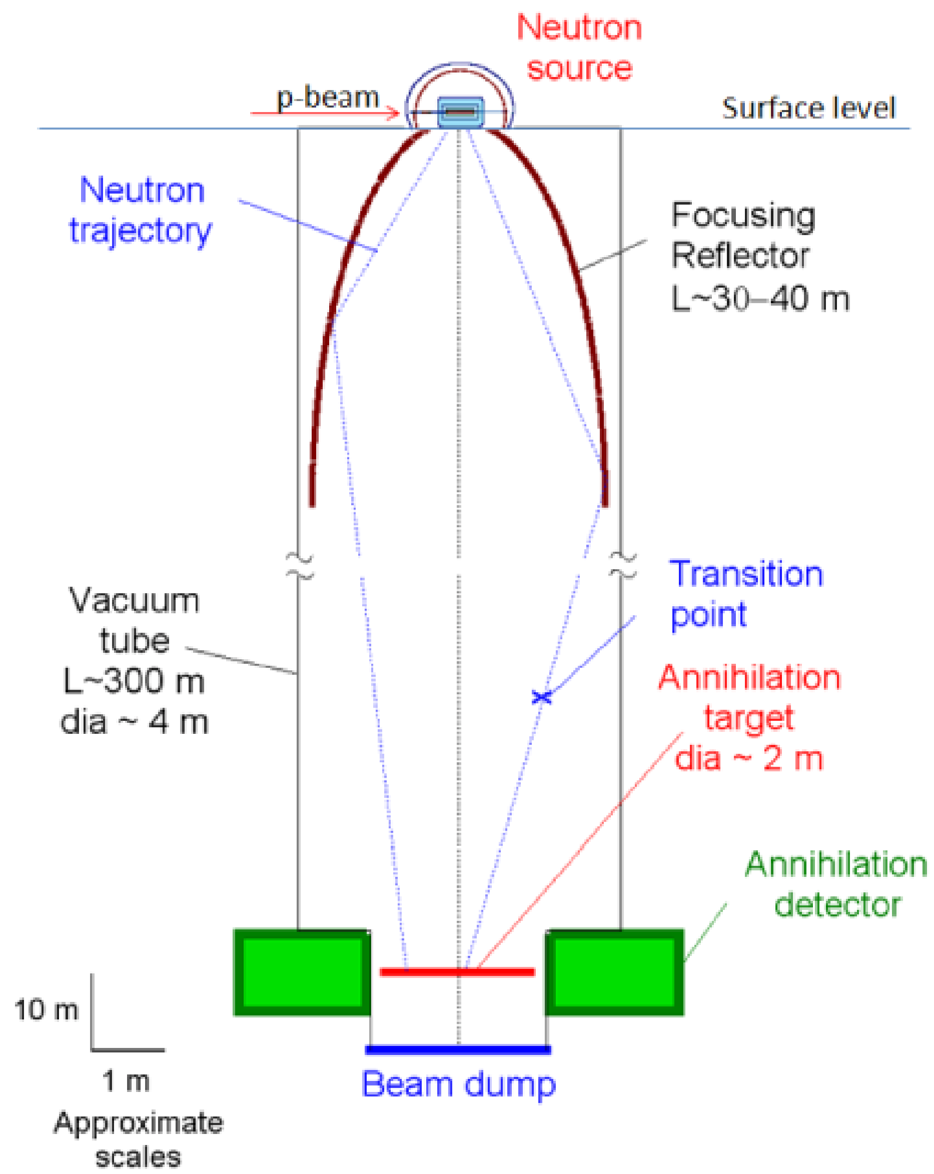
[1] *California State University, Domingues Hills*
[2] *Indiana University*
[3] *Los Alamos National Laboratory*
[4] *University of Maryland*
[5] *North Carolina State University*
[6] *NRC/NIST*
[7] *St. Petersburg Nuclear Physics Institute, Russia*
[8] *University of Tennessee*

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

N-Nbar search with a vertical layout at DUSEL

- Dedicated small-power cyclotron spallation source with cold neutron moderator → $V_n \lesssim 1000$ m/s
- Vertical shaft $\gtrsim$ 1000 m deep with diameter $\gtrsim$5 m
- Large vacuum tube 10^{-5} Pa, focusing reflector; Earth magnetic field compensation system to ~ nT
- Detector (similar to ILL N-Nbar detector) well-shielded at the bottom of the shaft (no new technologies)
- No background: one event→ discovery!

The possibility of a large increase in sensitivity of the experimental search for n →anti-n transition is a central motivation of NNbar DUSEL expt.



Sources of x1000 Improvement on ILL Experiment with Cold Neutrons

-increased phase space acceptance of neutrons from Source (current optics: m=3): x~60

-increase running time: x~3

-increase neutron free-flight time: x~100

-decreased source brightness :x~1/20

For horizontal experiment: greater source brightness ~counteracted by (dispersive) gravitational defocusing of Maxwellian neutron spectrum

Comparison

of the major parameters of the horizontal and vertical N-Nbar search experiments

Neutron source	RHF/ILL/Grenoble	HFIR/Oak Ridge (HB–3 beam)	Dedicated TRIGA reactor at DUSEL
Reference	M. Baldo-Ceolin et al., Z. Phys. C63 (1994) 409	W. Bugg et al, LOI UTK-PHYS-96-L1	D. Baxter et al, LOI-7 DUSEL Homestake PAC, 2006
Layout	Horizontal	Horizontal	Vertical
Status	Completed experiment	Reactor is unavailable	Letter of Intent
Data	From experiment	Simulations	Simulations
Reactor power (MW)	**58**	(85) **100**	**3.5**
Reactor's peak thermal n-flux	**$1.4 \cdot 10^{15}$** (n/cm^2/s)	**$1.5 \cdot 10^{15}$** (n/cm^2/s)	**$1.5 \cdot 10^{13}$** (n/cm^2/s)
Moderator	Liquid D_2	Supercritical H_2	Liquid D_2
Source area	6×12 cm^2	~ 11 cm dia.	20 cm dia
Target diameter	1.1 m	2.0 m	2.0 m
Flight path	76 m	300 m	1000 m
Neutron fluence @ target	$1.25 \cdot 10^{11}$ n/s	~ $8.5 \cdot 10^{12}$ n/s	4.2×10^{11} n/s
Average time of flight	0.109 s	0.271 s	1.5 s
Detector efficiency	0.48	~ 0.5	0.5
Operation time (s)	$2.4 \cdot 10^7$	$7 \cdot 10^7$ (~3 years)	$7 \cdot 10^7$ (~3 years)
$\tau_{n\bar{n}}$ limit (90% CL)	$8.6 \cdot 10^7$ s	$3.0 \cdot 10^9$ s	$3.0 \cdot 10^9$ s
Discovery potential per second	$1.5 \cdot 10^9$ n·s^2/s	$6.2 \cdot 10^{11}$ n·s^2/s	6.5×10^{11} n·s^2/s
Sensitivity	**1**	**410**	**430**

For *one day* of operation in a new proposed N-Nbar search experiment one can obtain the same sensitivity as for *one year* in the previous RHF/ILL-based experiment in Grenoble.

Supermirror Neutron Optics: Elliptical Focusing Guides

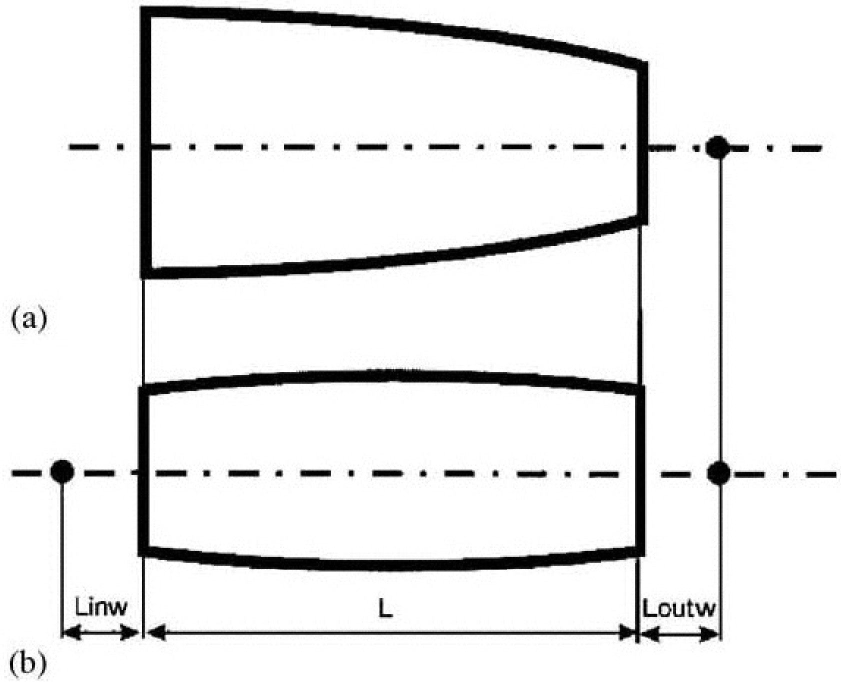


Fig. 1. Parameters for the (a) parabolic and (b) elliptic focusing guide in the x-plane.

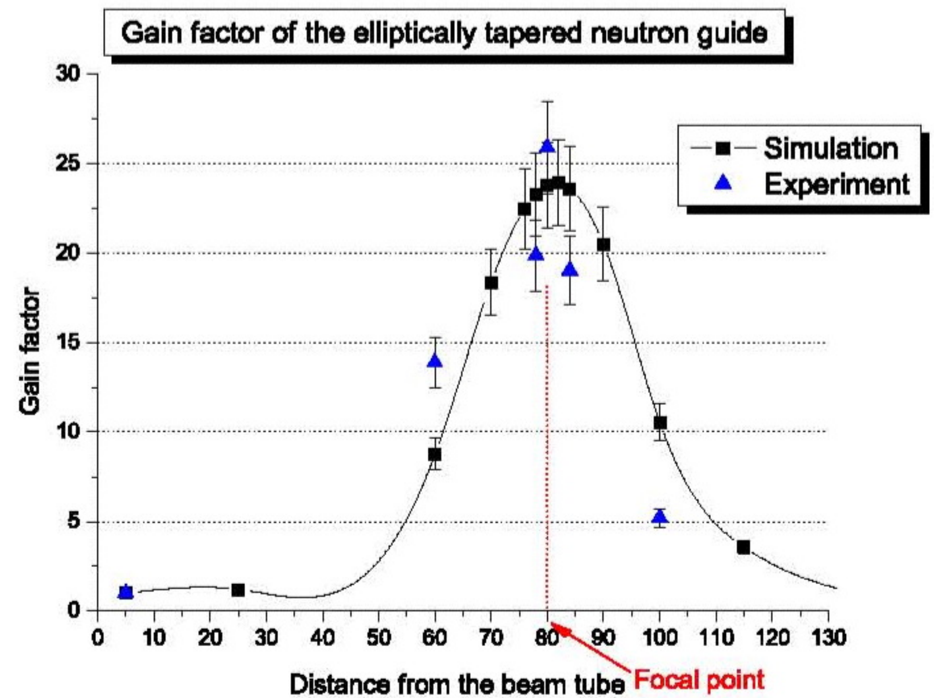


Fig. 3. Neutron intensity as measured and calculated versus distance from the exit of the guide. Clearly seen is the point of maximum intensity near $F_2 = 80\,\mathrm{mm}$.

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

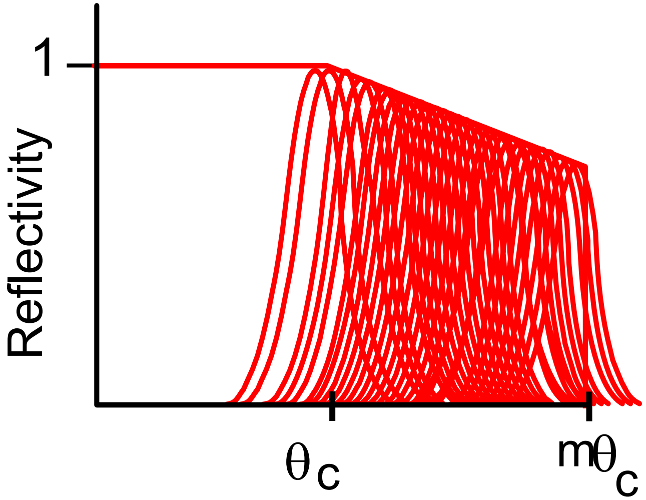
Under development for neutron scattering spectrometers

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

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

Commercial Supermirror Neutron Mirrors are Available With $m \approx 3$ - 4.

Phase space acceptance for straight guide $\propto m^2$, more with focusing reflector



Multilayer mirror

"Items of commerce"

<u>Engineering R&D issues @DUSEL:</u>

(1) Mechanical support of large vertical neutron reflector in tube

(2) Assembly of reflector into tube

Thermal Neutron Source

- Cold flux required ~1/10 of SINQ at PSI, *i.e.* 100 kW or less spallation target, standard cold source technology

- Compact Superconducting Cyclotron (CSC) technology under development has performance targets far in excess of this requirement, with potentially very inexpensive accelerators (20 M?); Phys. Rev. Lett **104**, 141802 (2010).

- Other projects may also require accelerators on site at DUSEL (*eg* Daeδalus) – NNbar a tiny fraction of required output

New cost estimate, September 2010

Preliminary cost estimate for N-Nbar DUSEL project with high-current accelerator as a neutron source

Disclaimer: this cost estimate is prepared without the benefit of detailed preliminary engineering studies

Assumptions:

DUSEL laboratory infrastructure, buildings, access roads are not included

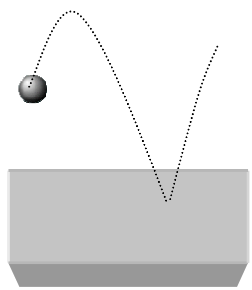
Vertical shaft at DUSEL (~ 1 km long) is available

Possible accelerator configurations are discussed in http://arxiv.org/abs/1006.0260 (see section 3.1)

#	Description	Estimate $M	Basis for estimate
1	1 MW high-current accelerator	20	Phys.Rev.Lett.104:141802,2010.
2	Spallation target + cold source	10	educated guess ↓
3	Vertical shaft outfitting	6	
4	Vacuum vessel and active magn. shield	8	
5	Passive 1-km magn shield	9	
6	Focusing reflector	8	
7	Reflector and shield mech. support	4	
8	Vacuum system	8	
9	Detector and electronics	8	
10	Experimental systems	7	(in Minos 40% of total)
11	Outfitting for undergraound accupancy	2	
12	Furniture, fixtures & equipment	1	
13	Design and Engineering (~10% of above)	9	
14	Contingency (~30% of above)	30	
	Total	130	

Another Possibility: Ultracold Neutrons?

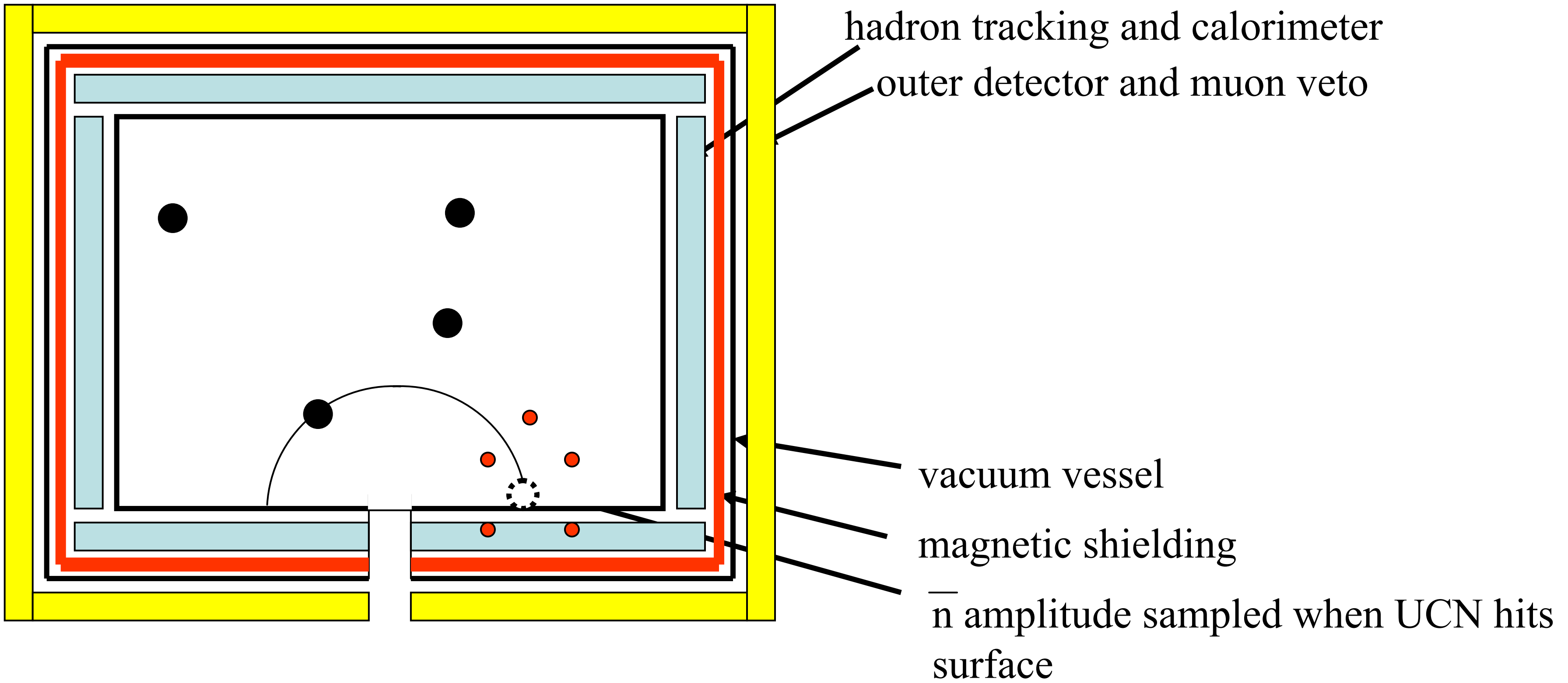
- UCN : K.E. < $V_{Fermi} \leq$ 340 neV
  reflect, for any angle of incidence, from some material surfaces→can be stored for times comparable to the β-decay lifetime in material bottles!



- Materials with high V_{Fermi} :
  Diamond like carbon → $V_F \leq$ 300 neV
  ^{58}Ni →$V_F \leq$ 340 neV

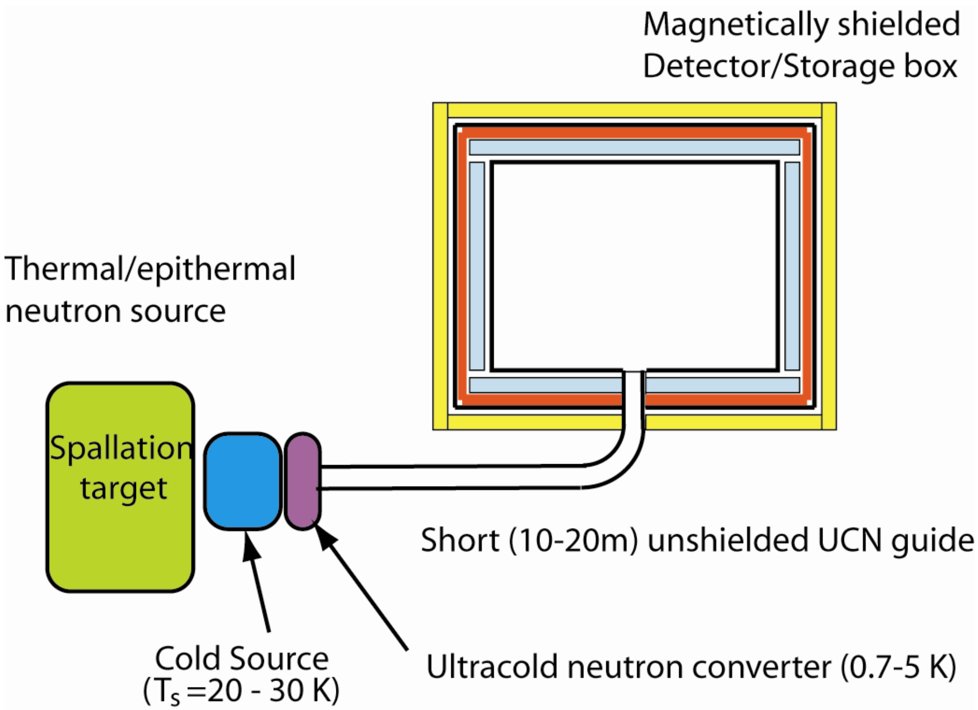
- A number of very strong UCN sources are coming on line in the next 5-6 years

NNbar with UCN



Box filled with UCN gas…many samples/neutron
longer average flight times (~1/3 sec)
large neutron current required

Pros and Cons



Advantages:

- No long, shielded beamline required: **more compact and less $**
- Sources soon available: **much less expensive**
- Same ability to turn “on” and “off” effect w/magnetic field

Disadvantages:

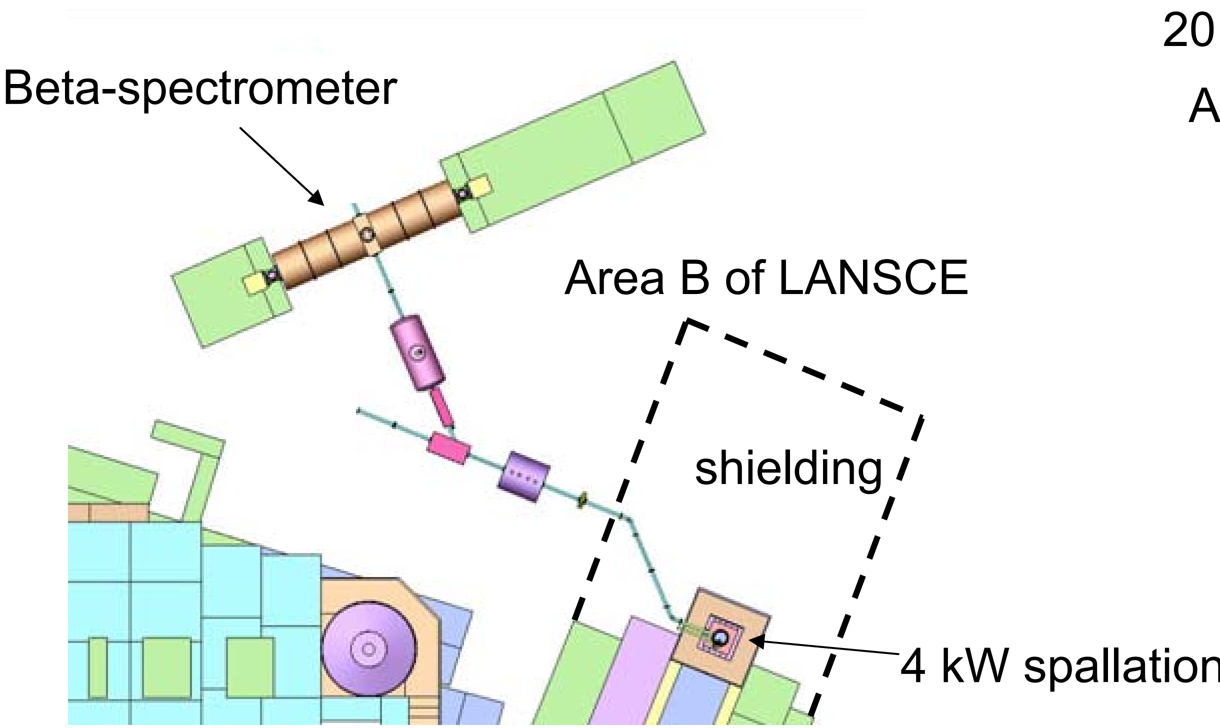
- Limits less stringent than those obtained with CN beam geometry

Possible UCN sources

- ILL: 3×10^6 UCN/s available now
- **Potentially competitive SD_2 sources**:
  - PULSTAR reactor w/ 3.5 MW upgrade: 1.2×10^7 UCN/s
  - PSI (10-20 kW spallation target– 1 MW peak): 5×10^9 in close-coupled storage volume, every 4 to 8 minutes; operation in 2011
  - FRM II reactor (24 MW): perhaps 4×10^7 UCN/s; begin operation roughly 2012 (project funded 2007)
- **LHe superthermal sources**
  - TRIUMF (5-10 kW spallation target; 50 kW peak): 5×10^7 UCN/s
  - Dedicated 1.9K source (200 kW): 3.3×10^8 UCN/s

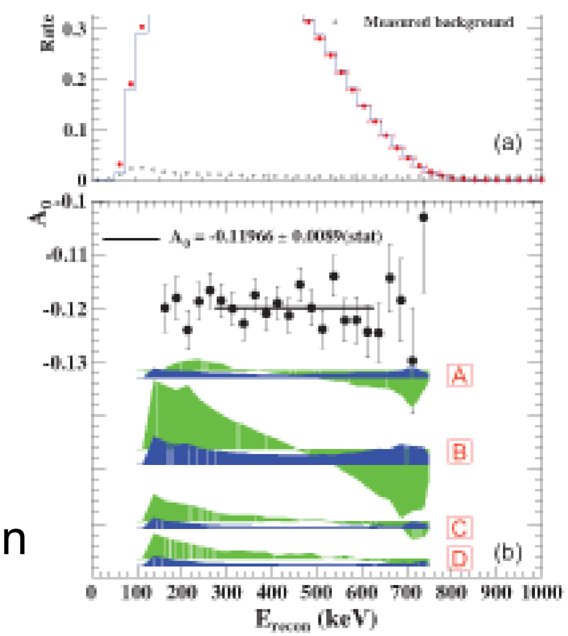
SD_2 Source Development: UCNA

- First angular correlations in polarized n beta-decay using UCN (P effectively 100%, negl. n backgrounds)
- First experiment to implement a spallation-driven SD_2 source and understand lifetime of UCN in SD_2
  - High production rate in SD_2, but UCN lifetime relatively short
  - 5K operation, large heat cap makes cryogenics straightforward



2010: $g_A/g_V = -1.27590^{+0.00409}_{-0.00445}$

ArXiv:1007.3790v1



UCNA Collaboration

California Institute of Technology

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University of Winnipeg

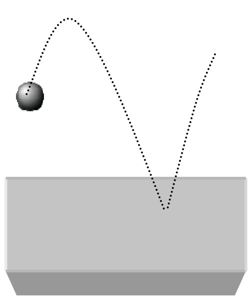
J. Martin

Virginia Polytechnic Institute and State University

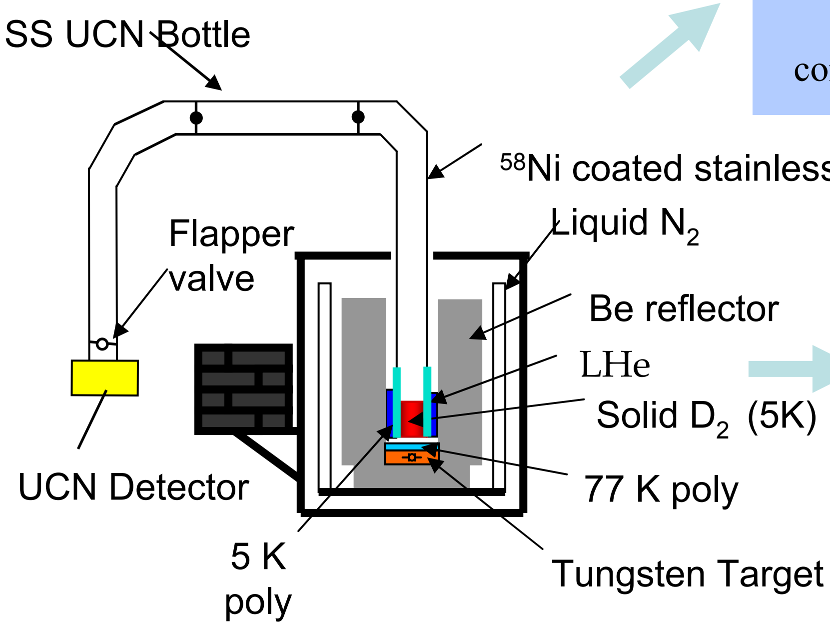
R. R. Mammei, M. Pitt, R. B. Vogelaar

Students in green

Underlined students from TUNL



Key UCNA SD_2 Prototype Results



$$\tau_{para} = 1.2 \pm .14\ (\text{stat}) \pm .20\ (\text{syst})\ \text{ms}$$

C. L. Morris *et al.*, Phys. Rev. Lett. **89**, 272501 (2002)

confirmed: F. Atchison et al., Phys. Rev. Lett. **95**, 182502 (2005)

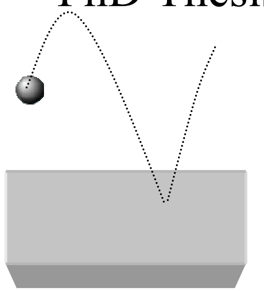
$$\rho_{UCN} \rightarrow 145 \pm 7\ \text{UCN/cm}^3$$

A. Saunders *et al.*, Phys. Lett. B **593**, 55 (2004)

confirmed: F. Atchison et al., Phys. Rev. C. **71**, 054601 (2005)

Recent update: C.-Y. Liu *et al.*, ArXiv:1005.1016v1

PhD Thesis: Chen-Yu Liu



Diamondlike Carbon Films

300 neV $> V_{fermi} >$ 270 neV, specularity > 99%, lpb < 10^{-4}

PhD Thesis: Mark Makela

PULSTAR Source Collaboration

- NCState Physics Department:

  R. Golub, P. Huffman, A. R. Young and graduate students, C. Cottrell, G. R. Palmquist, Y.-P. Xu

- NCState Nuclear Engineering Department:

  B. W. Wehring, A. Hawari, E. Korobkina

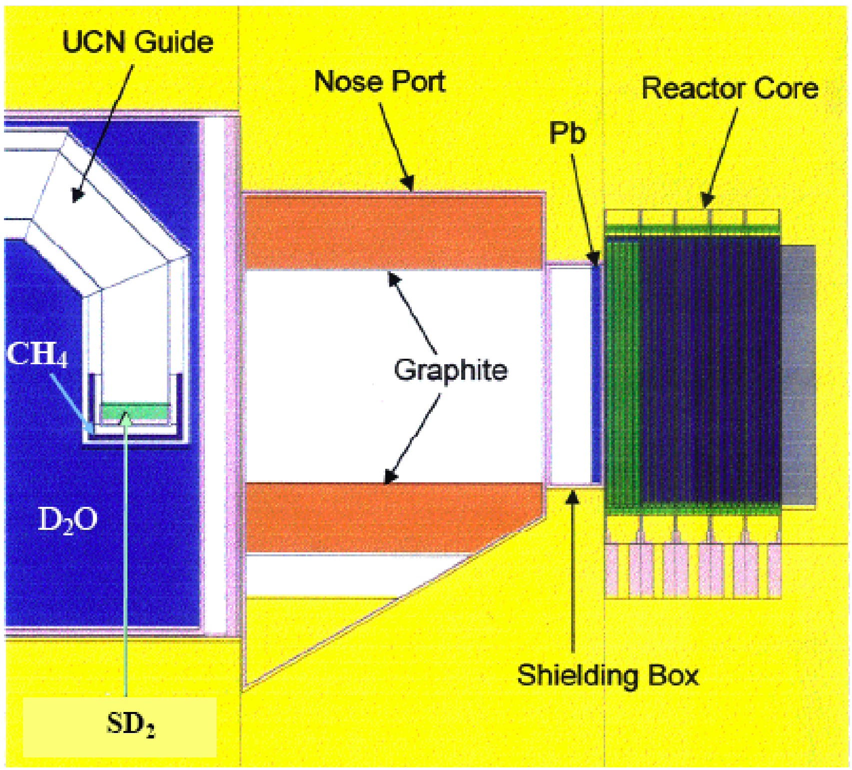
- PULSTAR technical staff

  A. Cook, K. Kincaid, G. Wicks

Local research groups with overlapping interests:

- H. Gao
- T. Clegg (weak interactions res.)

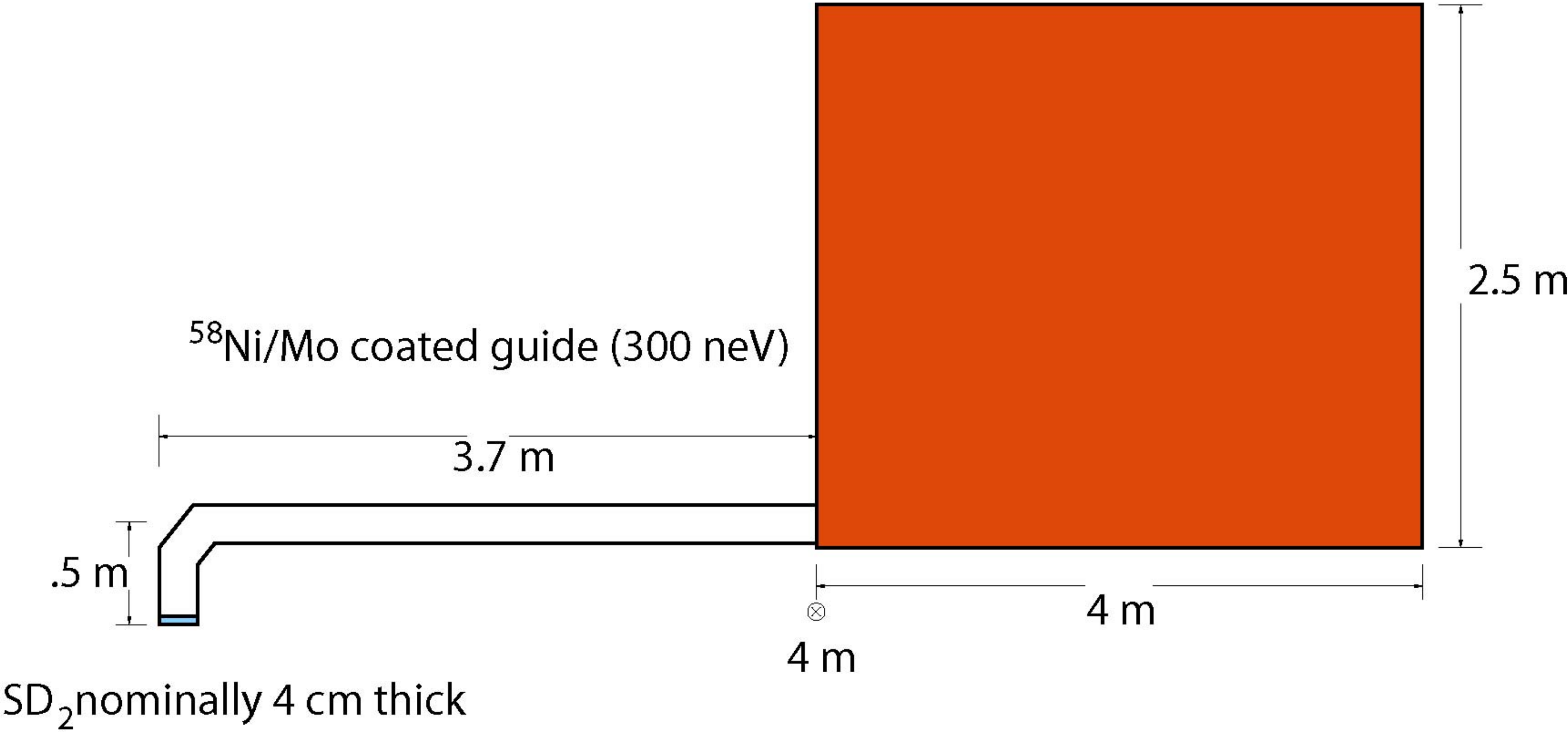
NCSU PULSTAR Source Schematic



- 1 MW (funding for 2 MW upgr)
- Floodable Helium Nose Port
- Heavy Water Thermal Moderator
- ^{58}Ni-coated guides

UCN extracted from $SD_2 = 3\times10^6$ UCN/s

The geometry:



How do we model transport?

Preliminary results for base case (annhilation det eff = 1, 1 year running):

NCState geometry, 4 cm thick SD2, 18 cm guides, 0.050s SD_2 lifetime, model storable UCN

Primary flux: 1.2×10^7 (below 305 neV) -- 3.5 MW

Box loading efficiency: 30%

325s avg. residency in experiment

Best case: diffuse walls, specular floor

discovery potential = 2.3×10^9 Ns

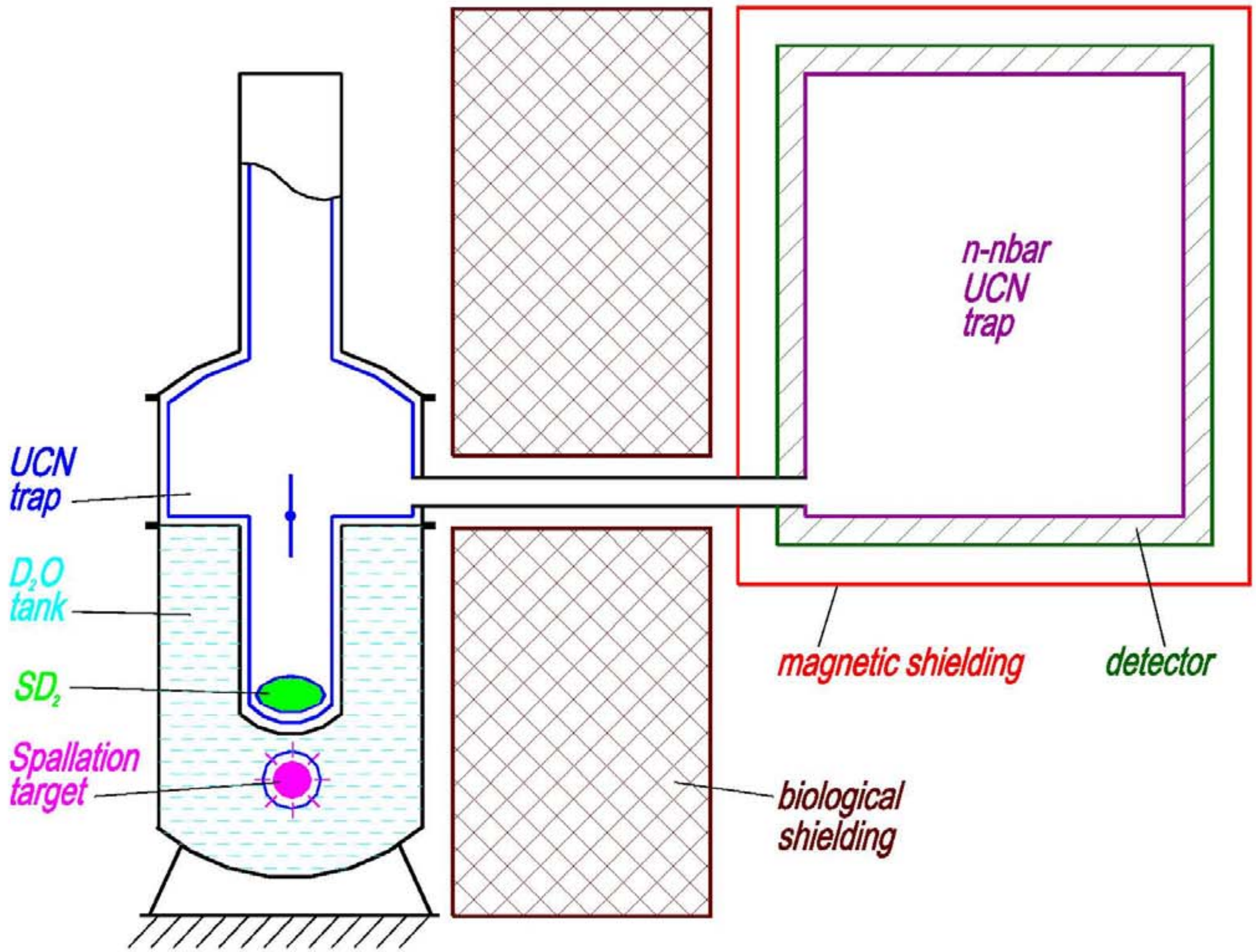
$\tau_{nn} > 1.1 \times 10^8$ s

Ultimate Reach with PULSTAR

- “straightforward gains”
  - 4 years of running

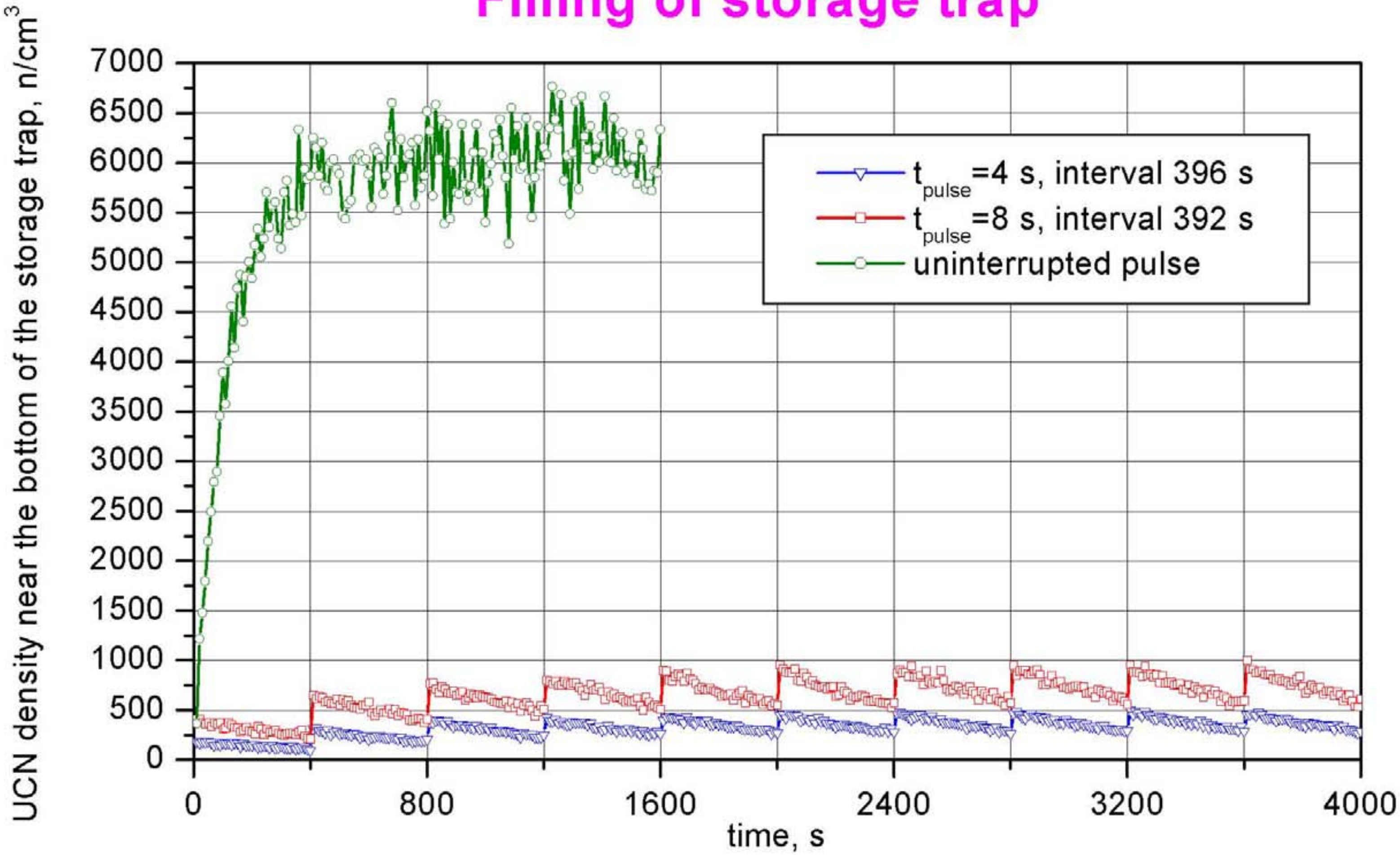
    $\tau_{nn} > 2.2\text{x}10^8$ s
- “speculative gains”
  - Multiple reflections (x1-4) Serebrov and Fomin; coherent n amplitude enhancement (x2) Golub and Yoshiki
  - Compound parabolic concentrators in floor
  - Optimized, higher “m” wall coatings
  - Solid oxygen source (C.-Y. Liu)
  - Larger vessel (requires modifications to facility)

Systematic studies of the PSI UCN source optimized for NNbar by A. Serebrov and V. Fomin

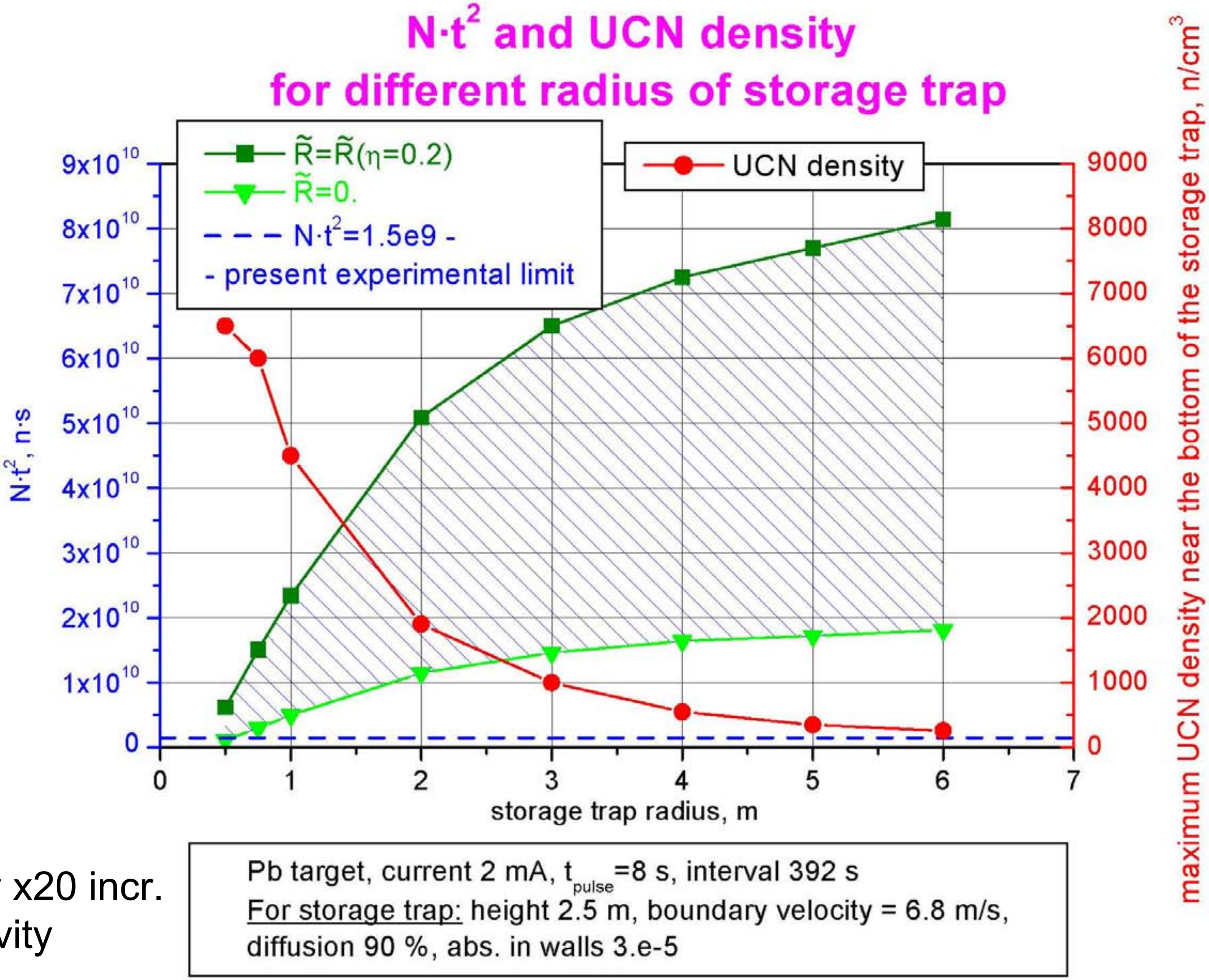


Mode of operation: beam pulsed w/ valve open, then valve closed and UCN stored in system (can, in principle, accumulate)

Filling of storage trap



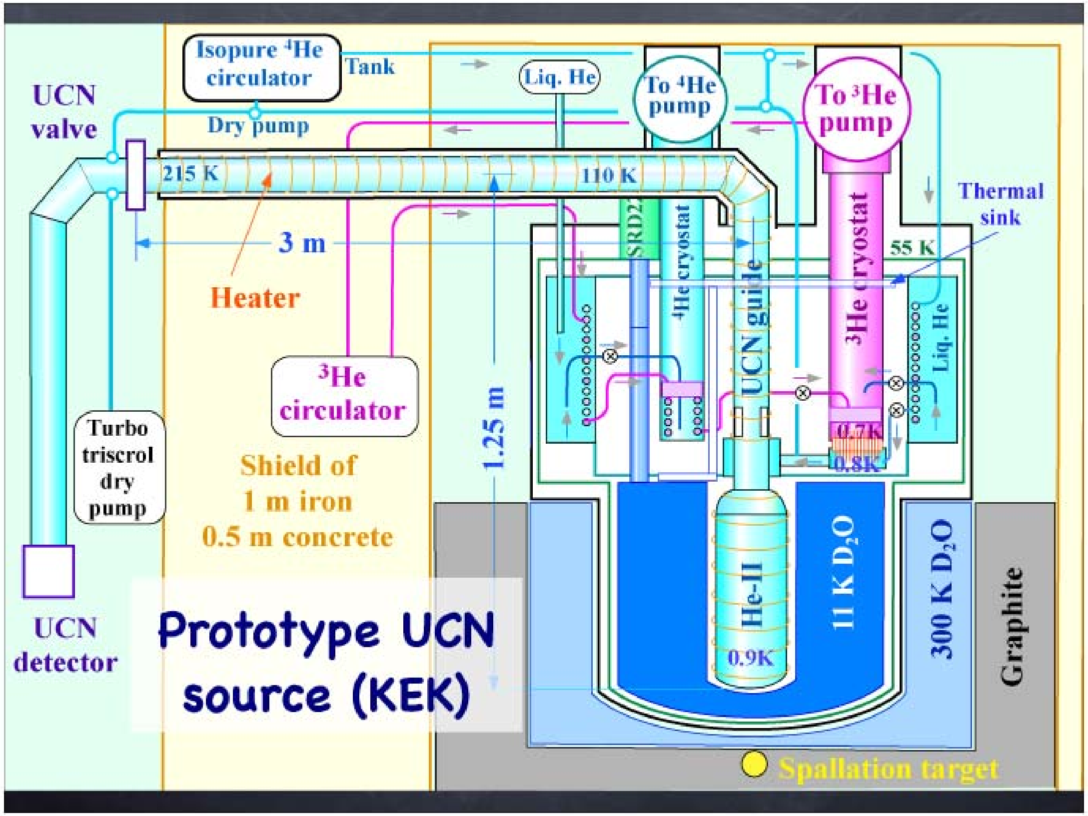
Pb target, current 2 mA
<u>For storage trap:</u> height 2.5 m, radius 3 m,
boundary velocity = 6.8 m/s, diffusion 90 %, abs. in walls 3.e-5



Roughly x20 incr.
In sensivity

Masuda: scaling RCNP He Source

Operating a prototype at the RCNP – basis for TRIUMF source



390 W spallation target

4×10^4 UCN/s

T < 0.9 K

BUT

Surprise: UCN lifetime still > 1s at 2K!
Makes high pressure, subcooled He source possible

UCN production rate in He-II for NNbar

1.2×10^{6} UCN/30 s (present exp)

x 512 x 2 x 8 x 1.3

(200kW) (horizontal) (D_2) (E_c 250neV)

= **4.2×10^{8} UCN/s** >> 1.2×10^{7} UCN/s for T_{NNbar} 3×10^{9} s ?

Production rate predicted

3.3×10^{8} UCN/s

2×10^{-9} Φ_n /cm^3/s x V cm^3 (V: He-II volume) by Golub

Φ_n = 1.7×10^{13} (n/cm^2/s) for V = 10^4 (cm^3) by Monte Carlo

Shielding scheme can increase volume

At 200 kW (CW), have 100 W of gamma heating (from MCNP)

subcooled superfluid He at 1.8-1.9 K in source

two-phase driven flow to refrigerator/liquifier…

should be possible!

Comparison (4y expt)

- PULSTAR (1.0 MW): $\tau_{nn} > 1.3 \times 10^8$ s
- PULSTAR (3.5 MW), optimized: $\tau_{nn} > 2.2 \times 10^8$ s
- SuperK: $\tau_{nn} > 2.7 \times 10^8$ s
- FRM II: $\tau_{nn} > 4 \times 10^8$ s (perhaps more)
- TRIUMF: $\tau_{nn} > 4.5 \times 10^8$ s
- PSI: $\tau_{nn} > 6.1 \times 10^8$ s
- 1.9K Superfluid He: $\tau_{nn} > 1.2 \times 10^9$ s
- Vertical CN beam: $\tau_{nn} > 3.5 \times 10^9$ s

These are very Interesting!

Staged Approach?

(1) Develop UCN experiment at Fermilab:

- 200 kW spallation target coupled to cold source
- 1.9K, high pressure, superfluid UCN converter with mixed phase coupling to cryogenics
- Modernize detector approach

(2) Move to DUSEL

- Keep target, source, converter and detector modules
- Install in existing vertical shaft

Intensity “frontier” for CN sources ~1 MW

→0.75 MW already demonstrated at the SINQ cold source

→Compatible with both cold and ultracold NNbar experiments (shielding approach required for UCN)

→Results in even greater sensitivity improvements!

Conclusions

- Motivation is strong for $N\bar{N}$
- Modest improvements (at least) in the free neutron oscillation time possible at various existing or planned UCN sources
- Stronger planned sources could be utilized for significant improvements in sensitivity to NN-bar oscillations
- The vertical CN source geometry appears to be the most sensitive approach, however it may be possible to adopt a staged approach to experimental development with significant improvements at each step!