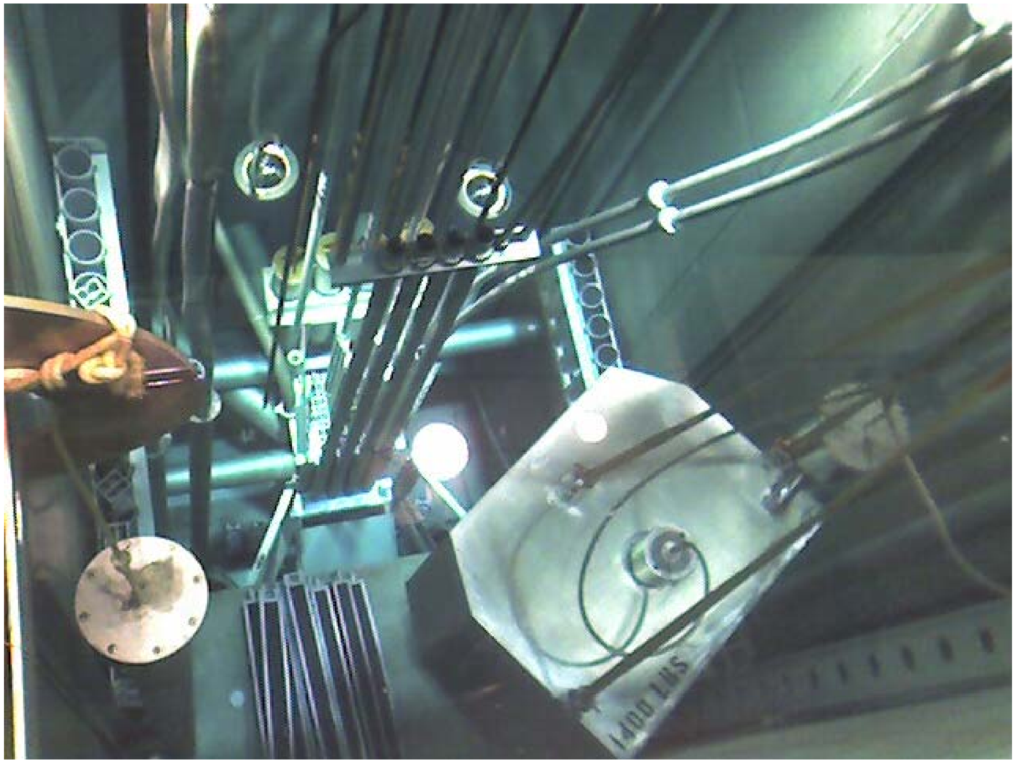
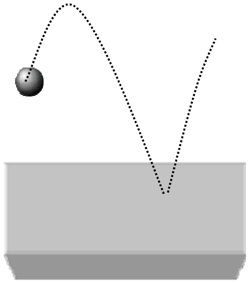
Ultracold Neutrons as Probes for Neutron-Antineutron Oscillations

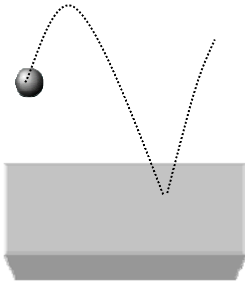


A.R.Young
NCState University



Outline

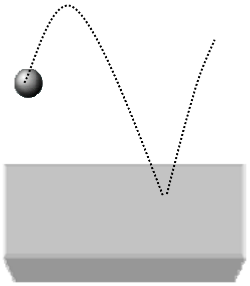
- What are ultracold neutrons?
- An N-Nbar experiment with ultracold neutrons
- Some source development background
- sources of UCN and achievable limits
- “Staged approaches” to N-Nbar experiments and opportunities for creativity



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} :

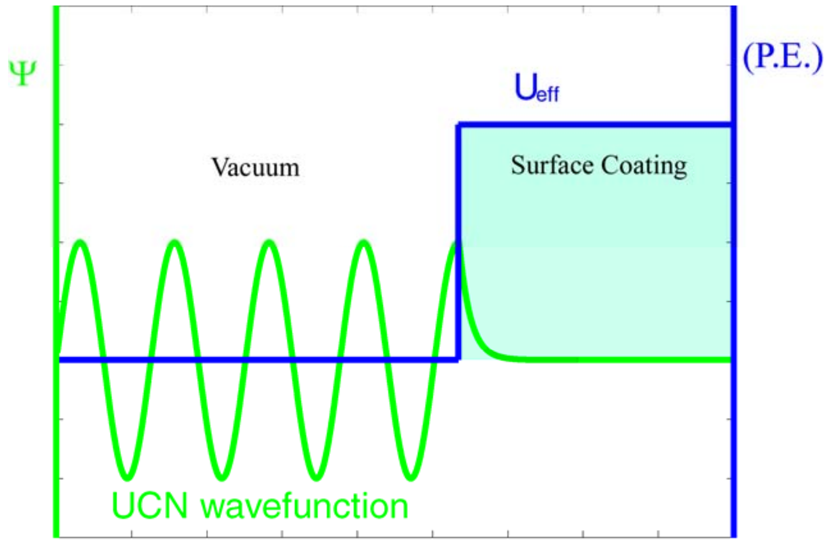
  Diamond-like carbon → $V_F \leq 300$ neV

  ^{58}Ni →$V_F \leq 340$ neV

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

Another way of thinking about it…

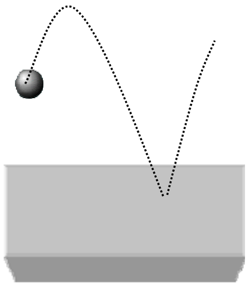
The UCN experiences an effective potential, U_{eff}, due to its interaction with nuclei on the surface…



Case where $E < U_{eff}$

If the kinetic energy of the UCN is less than the effective potential barrier at the surface, the UCN will be reflected for <u>any</u> angle of incidence…

One can store UCN in material bottles for <u>minutes</u> at a time!



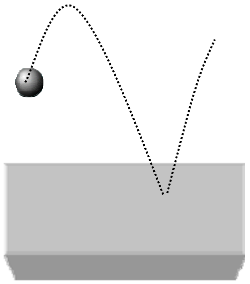
UCN Energy Scales

Energy of UCN moving 8 m/sec: 340 neV (nano-eV)
≈ 3.6 mK

Energy of UCN in 1T magnetic field: ± 60 neV

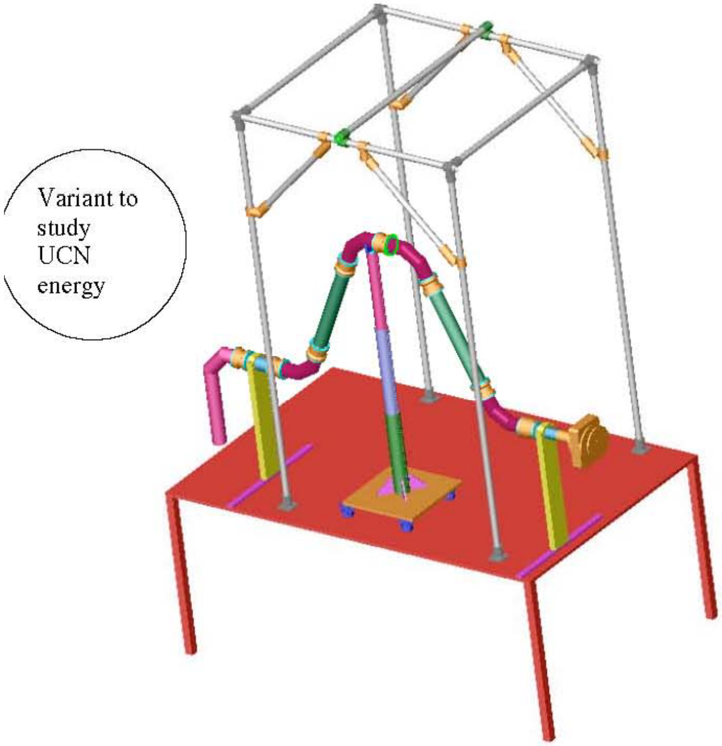
Energy change associated with a 1 m rise: 104 neV

→implications for optimized design of N-Nbar…
UCN can be polarized and stored using magnetic fields
Typical UCN can bounce no higher than about 3m!

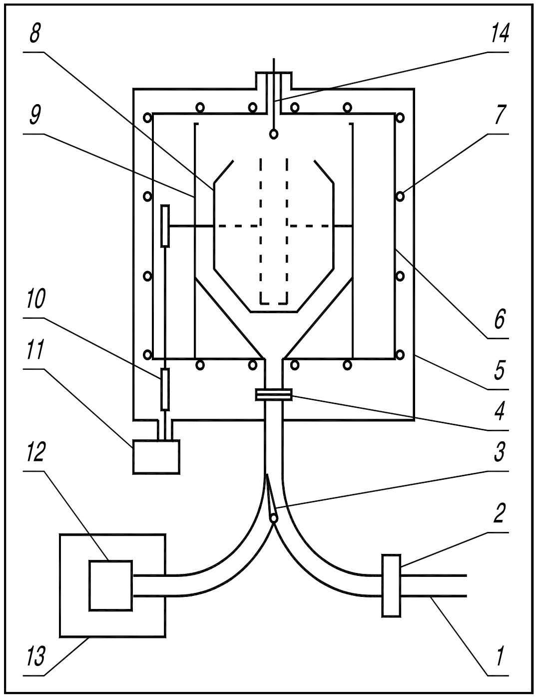


UCN Experiments Have a Unique Feel…

Lifetime Experiment (courtesy of A. Serebrov)



Variant to study UCN energy

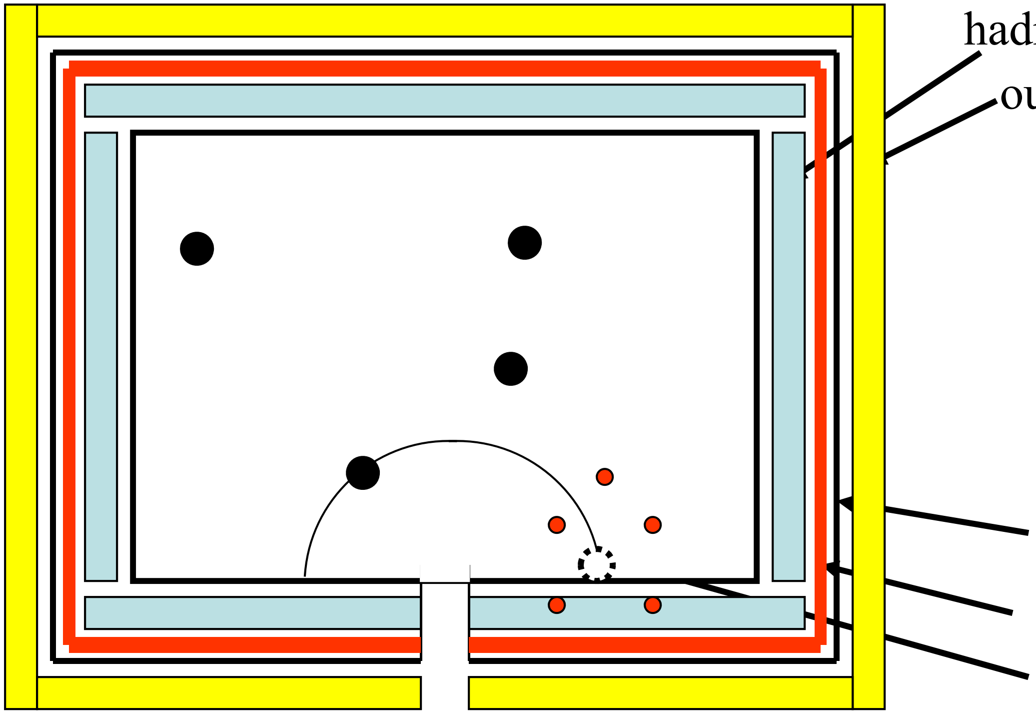


Rotating Tube = UCN Energy Spectrometer!

Courtesy of E. Korobkina

Giant “Kettle” to measure lifetime: Kettle rotated to pour UCN out in stages..

NNbar with UCN



hadron tracking and calorimeter

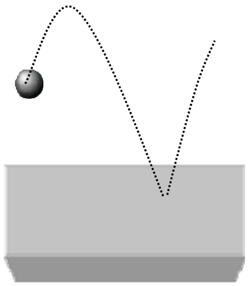
outer detector and muon veto

vacuum vessel

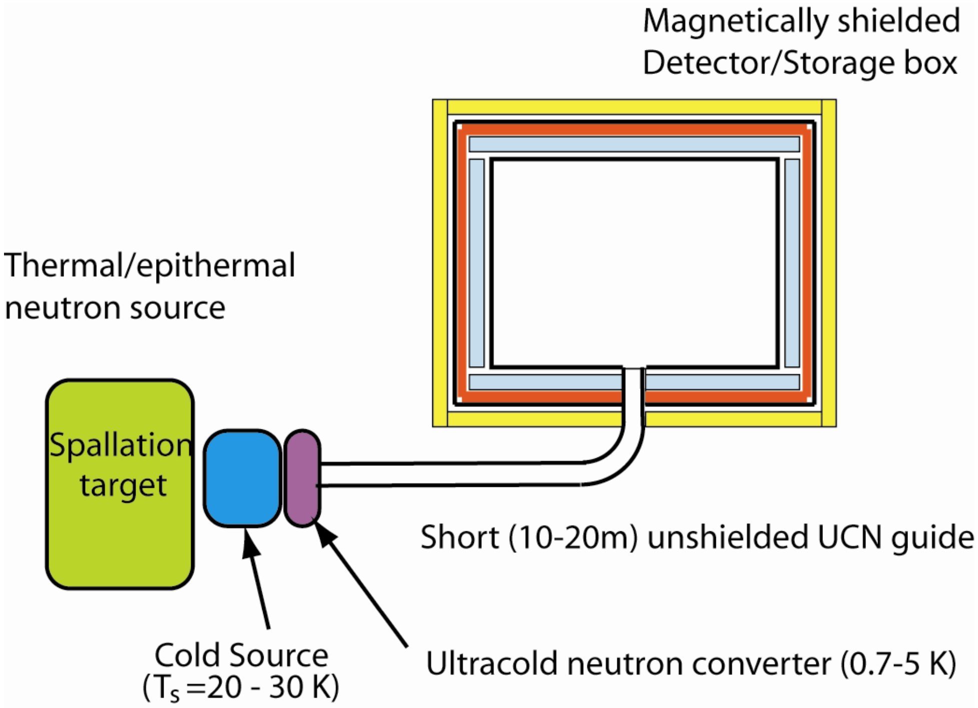
magnetic shielding

$\bar{n}$ amplitude sampled when UCN hits surface

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



Pros and Cons

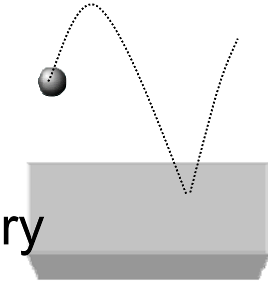


Advantages:

- No long, shielded beamline required: **more compact**
- Sources soon available: **much less expensive**
- Same ability to turn "on" and "off" effect w/magnetic field
- Almost "hermetic" detection of annhilation events

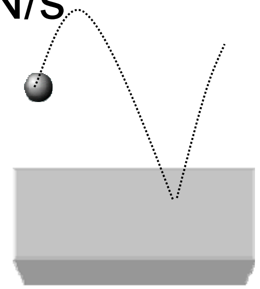
Disadvantages:

- Limits less stringent than those obtained with CN beam geometry



Possible UCN sources

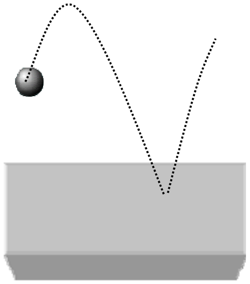
- ILL: 3x10^6 UCN/s available now
- **Potentially competitive SD_2 sources**:
  - PULSTAR reactor w/ 3.5 MW upgrade: 1.2x10^7 UCN/s
  - PSI (10-20 kW spallation target– 1 MW peak): 5x10^9 in close-coupled storage volume, every 4 to 8 minutes; operation in 2011
  - FRM II reactor (24 MW): perhaps 4×10^7 UCN/s; begin operation roughly 2012 (project funded 2007)
- **LHe superthermal sources**
  - TRIUMF (5-10 kW spallation target; 50 kW peak): 5x10^7 UCN/s
  - Dedicated 1.9K source (200 kW): 3.3x10^8 UCN/s



Solid Deuterium: UCN Source Development

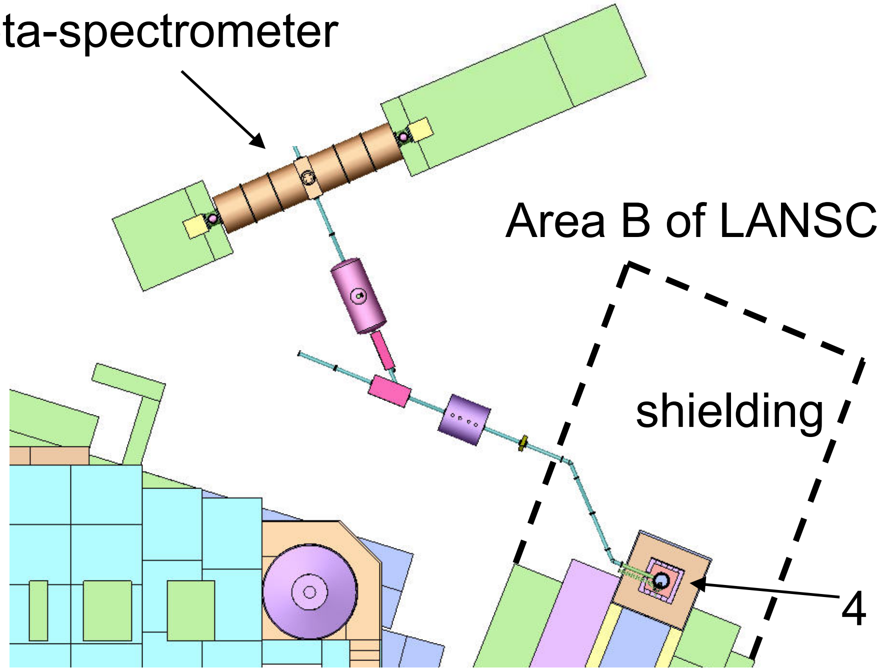
- Development of the UCNA solid deuterium source at LANL

- A follow-up: the PULSTAR solid deuterium source on NCSU campus



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



Beta-spectrometer

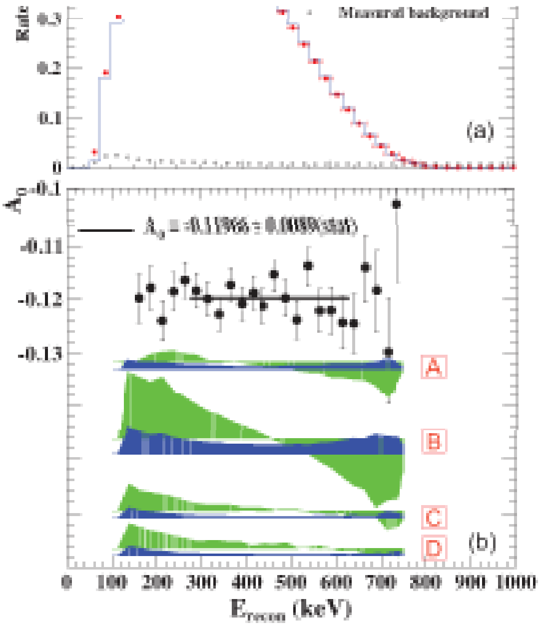
Area B of LANSCE

shielding

4 kW spallation

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

ArXiv:1007.3790v1



UCNA Collaboration

California Institute of Technology

R. Carr, B. Filippone, K. Hickerson, J. Liu, M. Mendenhall, R. Schmid, B. Tipton, J. Yuan

Institute Lau-Langevin

P. Geltenbort

Idaho State University

R. Rios, E. Tatar

Los Alamos National Laboratory

J. Anaya, T. J. Bowles (co-spokesperson), R. Hill, G. Hogan, T. Ito, K. Kirch, S. Lamoreaux, M. Makela, R. Mortenson, C. L. Morris, A. Pichlmaier, A. Saunders, S. Seestrom, W. Teasdale

North Carolina State University/TUNL/Princeton

H. O. Back, L. Broussard, A. T. Holley, R. K. Jain, C.-Y. Liu, R. W. Pattie, K. Sabourov, D. Smith, A. R. Young (co-spokesperson), Y.-P. Xu

Texas A&M University

D. Melconian

University of Kentucky

B. Plaster

University of Washington

A. Garcia, S. Hoedl, A. Sallaska, S. Sjue, C. Wrede

University of Winnipeg

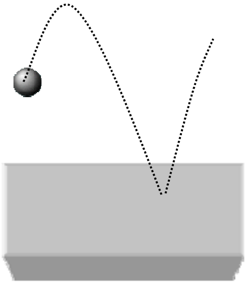
J. Martin

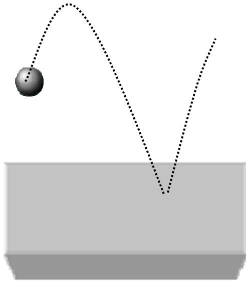
Virginia Polytechnic Institute and State University

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

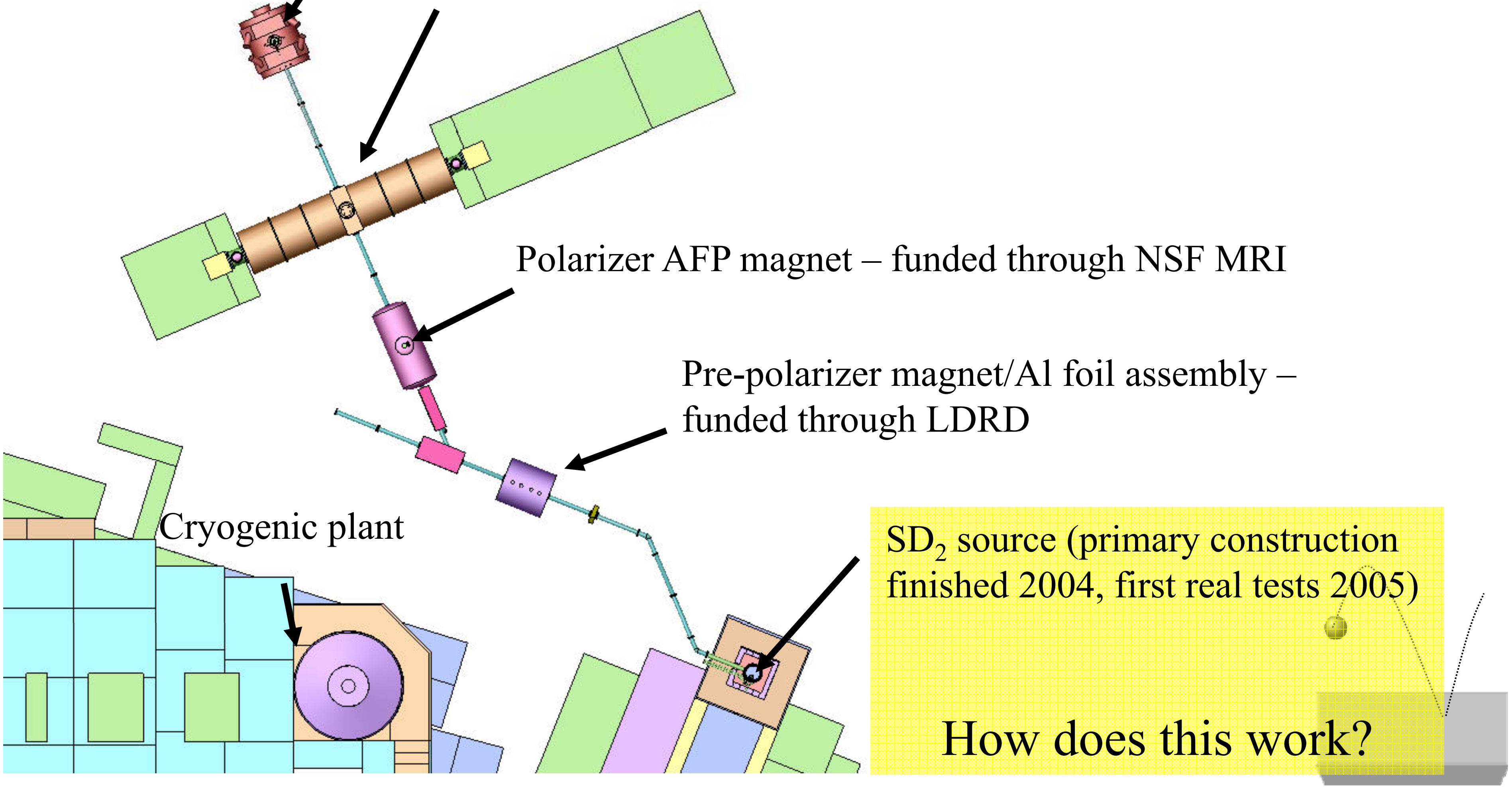
Students in green

Underlined students from TUNL





Major-System Status:



Possible analyzer magnet – availability/funding not yet determined

Spectrometer – funded through NSF MRI

Polarizer AFP magnet – funded through NSF MRI

Pre-polarizer magnet/Al foil assembly – funded through LDRD

Cryogenic plant

SD$_2$ source (primary construction finished 2004, first real tests 2005)

How does this work?

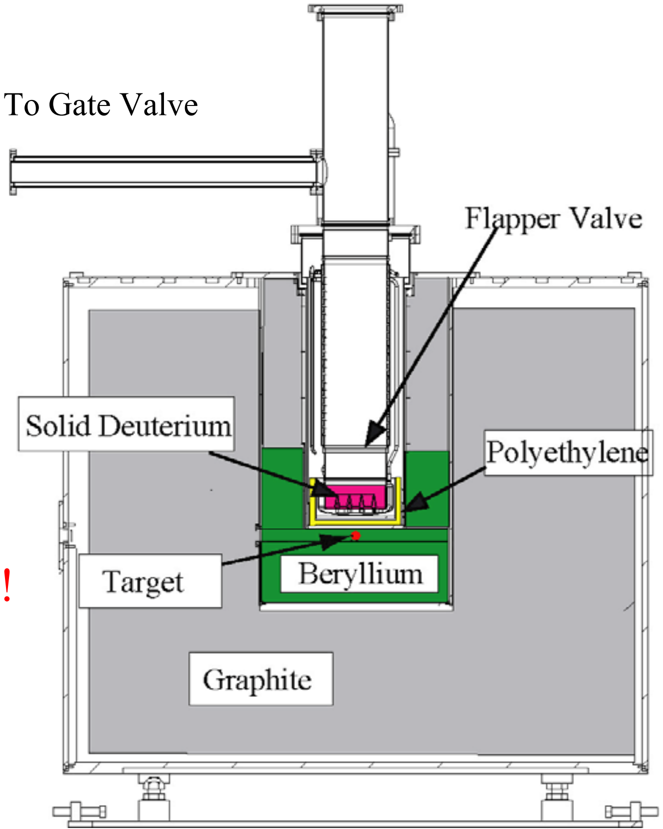
Loading the Decay Volume: SD_2 source facility

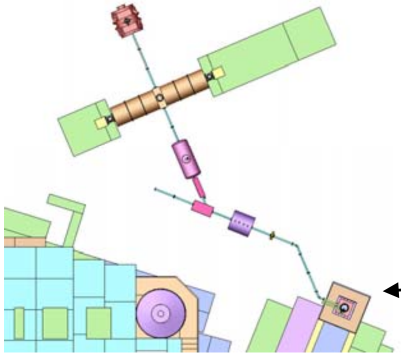
- 2005: no decays
  - replaced horizontal guides w/ SS
- 2006: 2 s^{-1}
  - current: <1μA →2μA, improved flapper
- 2007: 6 s^{-1}
  - current: →4μA, source volume 2l
- 2008: 15 s^{-1}
  - guides changed to DLC-coated EP Cu, geom C
- 2009: >30 s^{-1}
  - new target and improved upstream of AFP
- 2010: <60 s^{-1}

Equivalent to typical ILL expt!

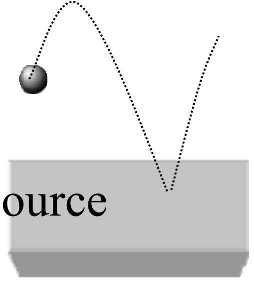
Looks promising!

Only source of extracted UCN in the US



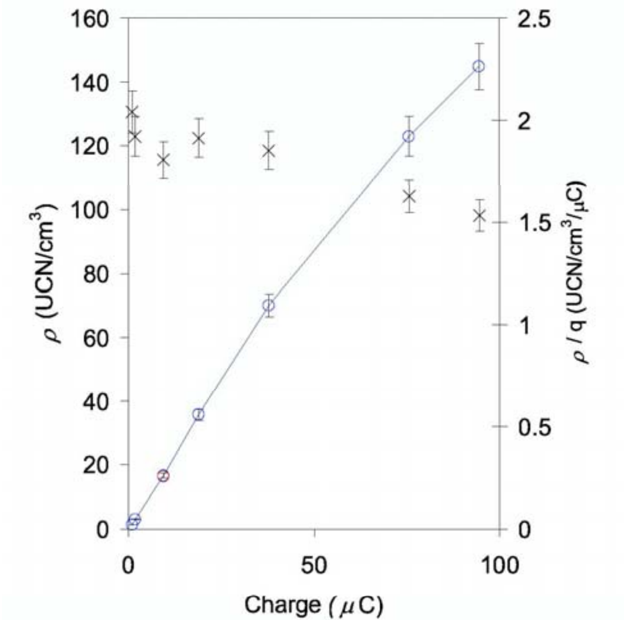


Solid deuterium source



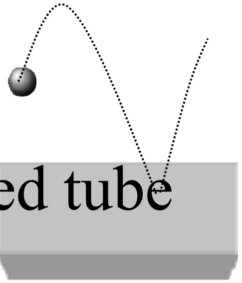
UCN Source and Transport

- Prototype source set world record for UCN production

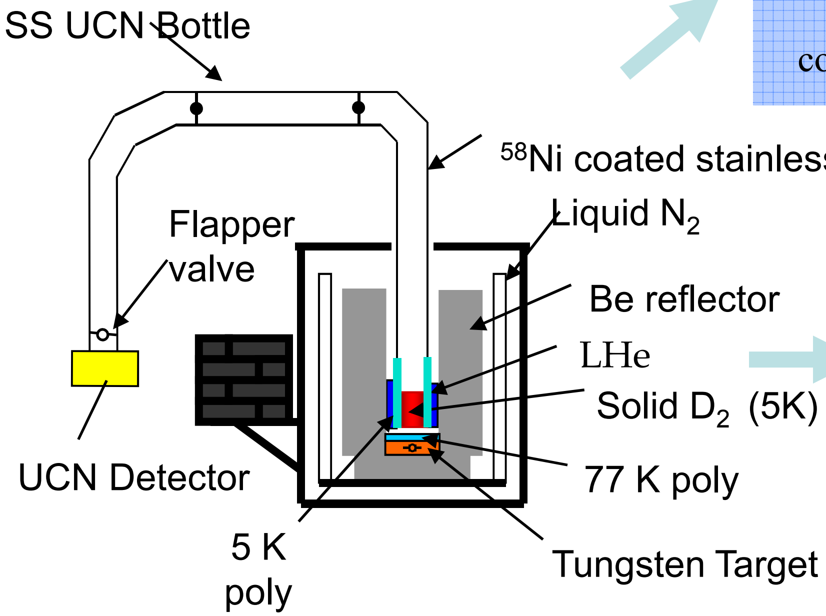


- Developed polarization preserving diamondlike carbon-coated guide tubes 95% transmission per meter – some of the best guides available

150 x 70 mm ID coated tube



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)

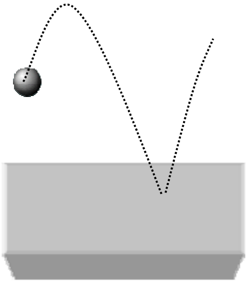
$$\rho_{UCN} \rightarrow 145 \pm 7\ \text{UCN/cm}^3$$

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

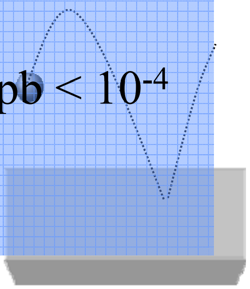
PhD Thesis: Chen-Yu Liu



Diamondlike Carbon Films

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

PhD Thesis: Mark Makela



Technical Aside on Production

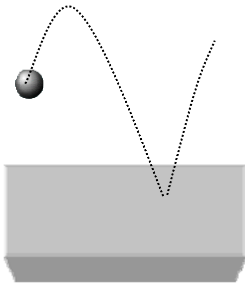
Using SD_2 as a generic example:

The UCN production rate from cold neutrons with energy E’ is proportional to

$$
\begin{aligned}
\left(\frac{d^2\sigma}{d\Omega dE'}\right)^{1\ phonon}_{J\rightarrow J'} &= \frac{k'}{k}\frac{\hbar^2\kappa^2}{2M_{D_2}}e^{-2W(\kappa)}S_{JJ'}(2J'+1)\\
&\times \sum_n\left(\frac{\hbar\kappa^2}{2M_{D_2}\omega}\right)^n\frac{1}{n!}\sum_{l=|J'-J|}^{J'+J}|A_{nl}|^2C'^2(JJ'l;00)\\
&\times \frac{Z(E_{ph})}{E_{ph}}\begin{cases} n(E_{ph})+1 & \text{if } E_{ph} >= 0\\ n(E_{ph}) & \text{if } E_{ph} < 0,\end{cases}
\end{aligned}
$$

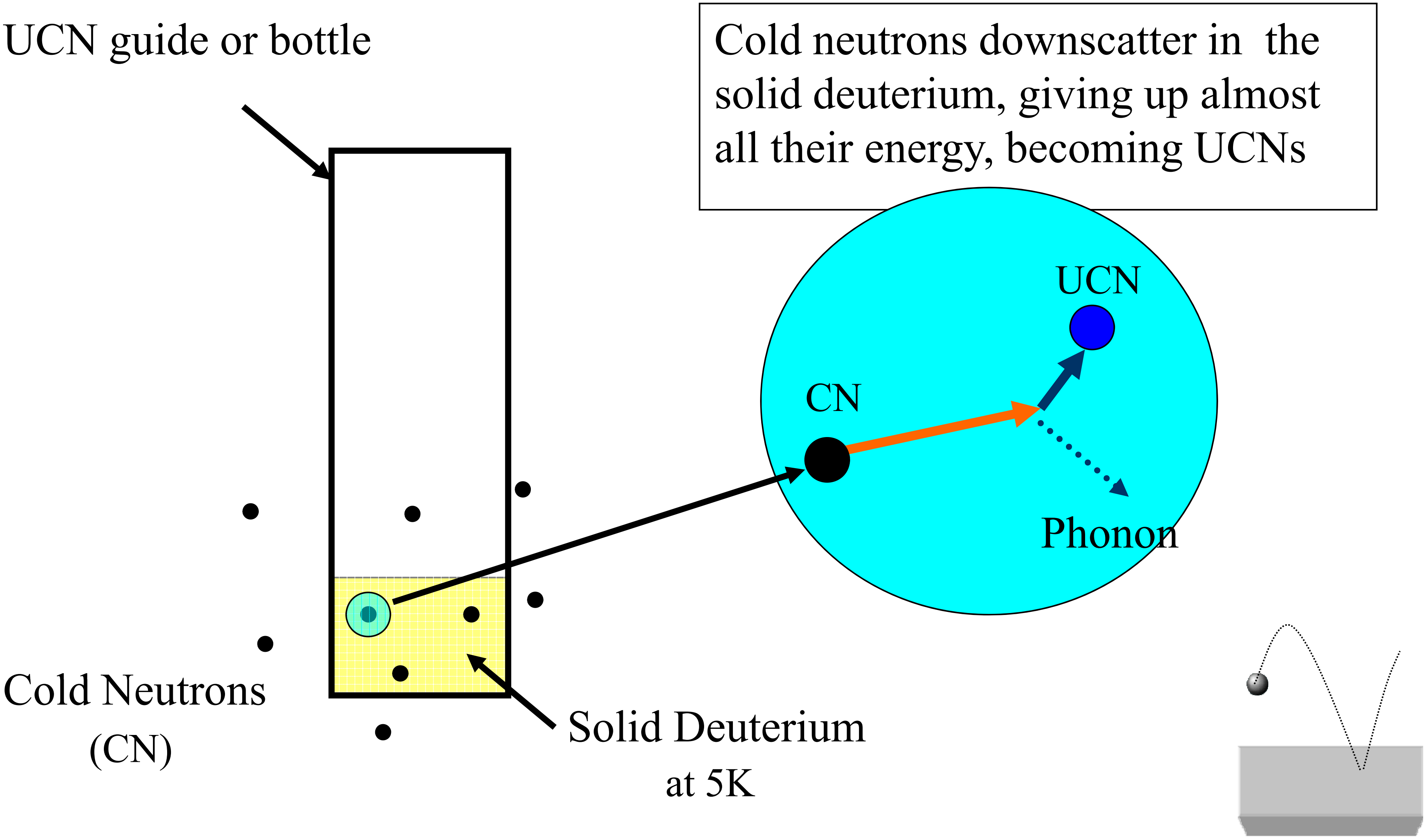
Favors low mass species

Favors low Debye T materials with good overlap with CN distribution (T ~ 20 – 30 K)



UCN Production

Inelastic scattering is dominated (He and ortho-Deuterium) by interactions with phonons



UCN guide or bottle

Cold neutrons downscatter in the solid deuterium, giving up almost all their energy, becoming UCNs

UCN

CN

Phonon

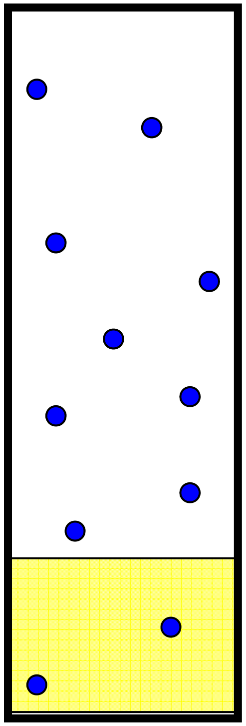
Cold Neutrons
(CN)

Solid Deuterium
at 5K

Achieving the Limiting Density

UCNs accumulate until the destruction rate in the source (N_{ucn}/τ) = the production rate (R)

$$N_{ucn}/\tau = R$$



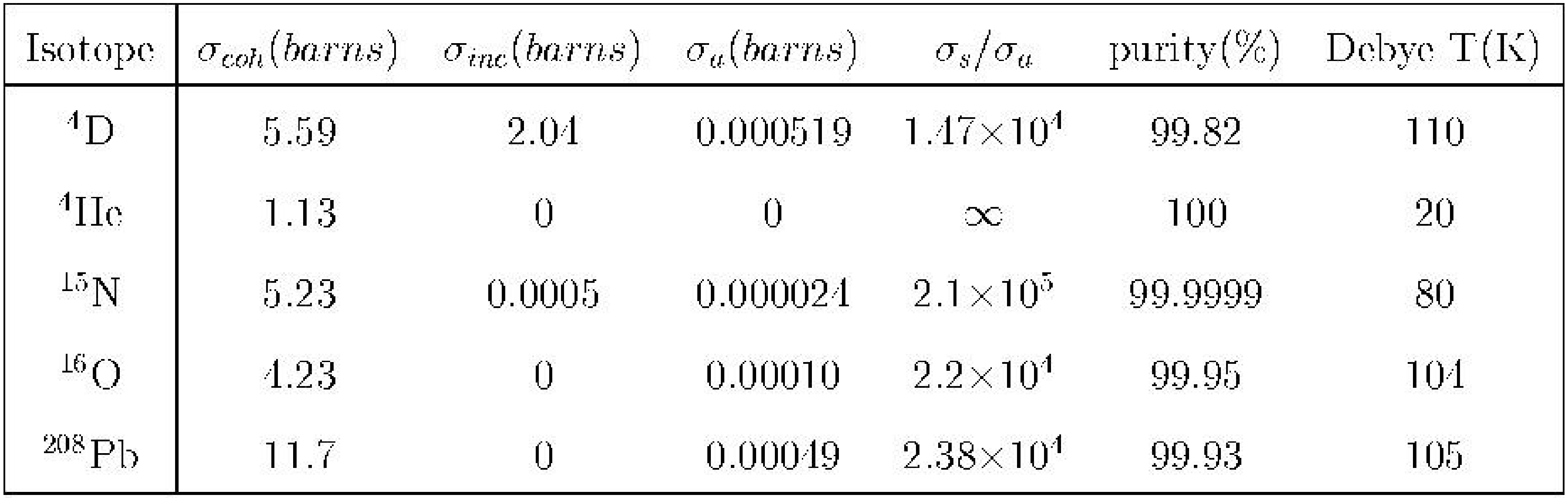
At this point, volume of bottle is full of UCNs with density N_{ucn}

$$N_{ucn} = R\tau$$

Lifetime of UCNs in source, is a critical parameter in the establishment of large UCN densities

Superthermal Source Candidates

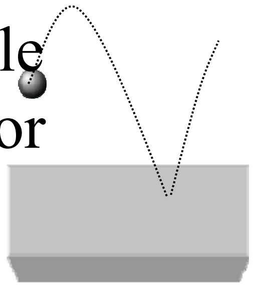
Need very low neutron capture cross-sections!



Isotope	$\sigma_{coh}(barns)$	$\sigma_{inc}(barns)$	$\sigma_a(barns)$	σ_s/σ_a	purity(%)	Debye T(K)
^{4}D	5.59	2.04	0.000519	1.47×10^4	99.82	110
^{4}He	1.13	0	0	∞	100	20
^{15}N	5.23	0.0005	0.000024	2.1×10^5	99.9999	80
^{16}O	4.23	0	0.00010	2.2×10^4	99.95	104
^{208}Pb	11.7	0	0.00049	2.38×10^4	99.93	105

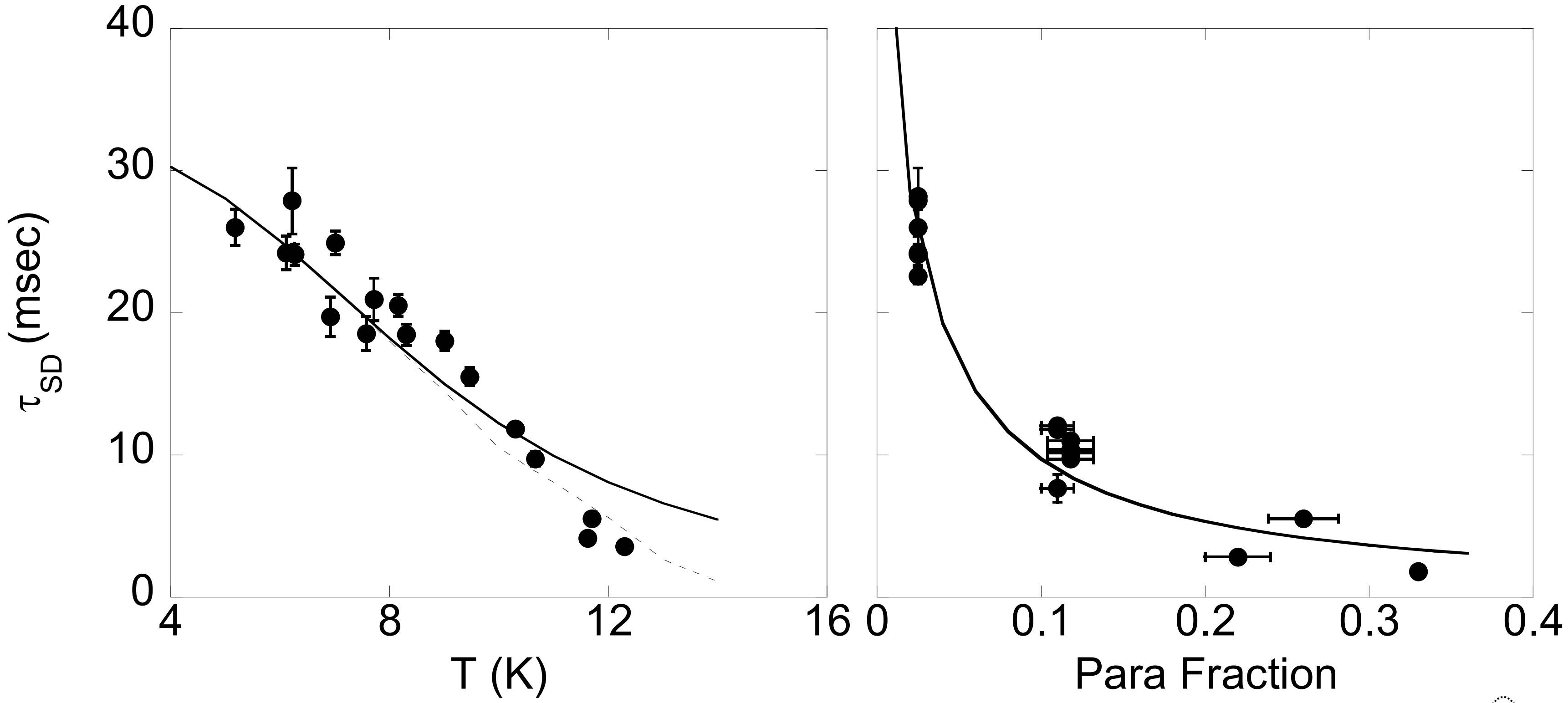
Table 7.1: Candidates for a superthermal source[8].

- He has (by far) longest absorption time: high densities accessible
- D_2 has larger cross-sections: higher production rates accessible (good for flow-through experiments, such as the one we plan for LANL)

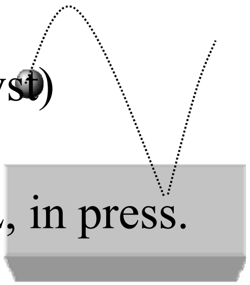


Prototype Source Key Results

Measured for the first time: UCN lifetime in SD_2



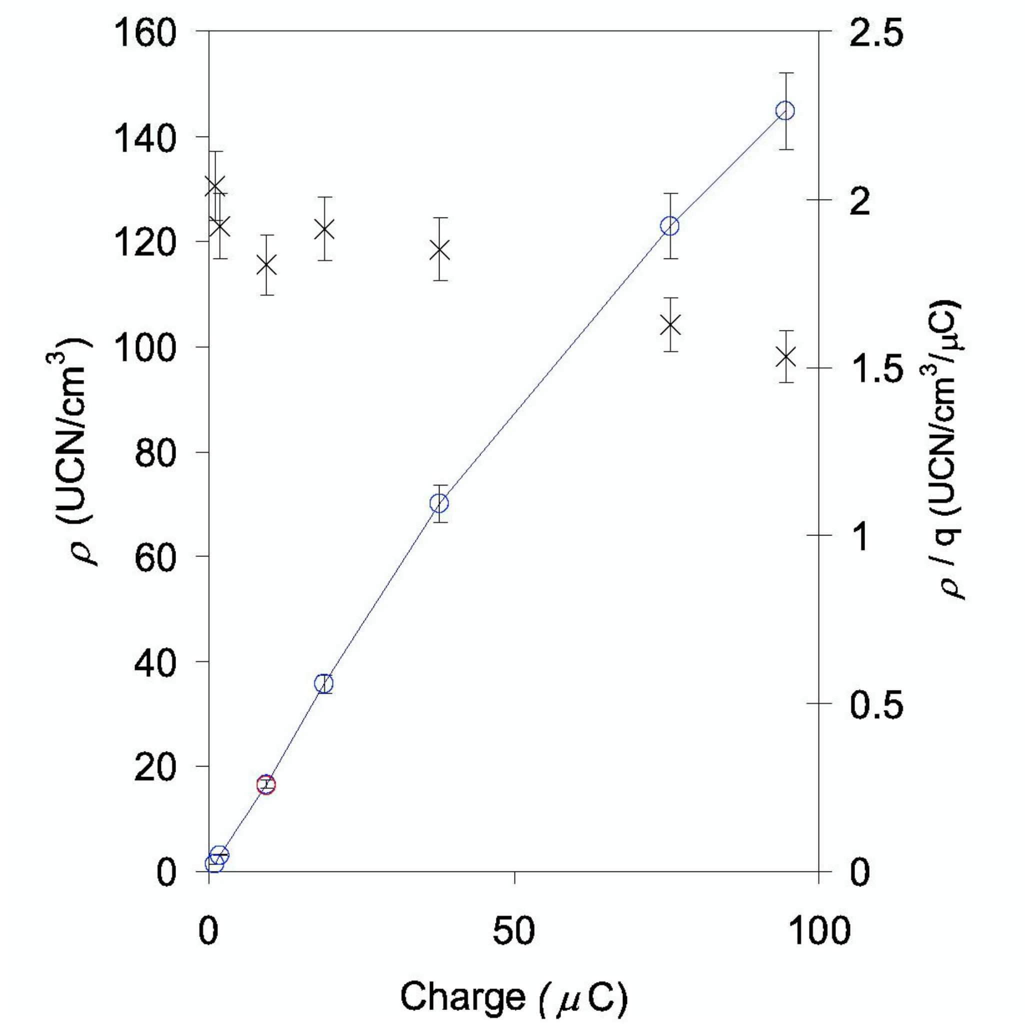
$\tau_{para} = 1.2 \pm .14\ (\text{stat}) \pm .20\ (\text{syst})$



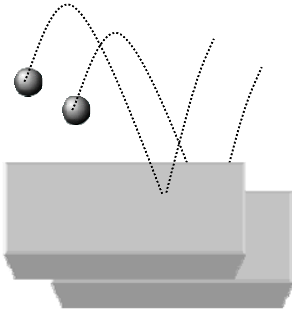
PhD Thesis: Chen-Yu Liu

C. L. Morris *et al.*, PRL, in press.

Very high densities achieved



Compare to previous record for bottled UCN of
41 UCN/cm^3 (at ILL)



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:

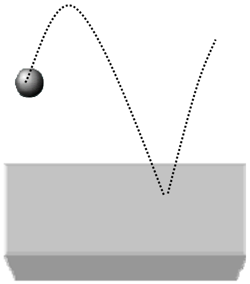
  B. W. Wehring, A. Hawari, E. Korobkina

- PULSTAR technical staff

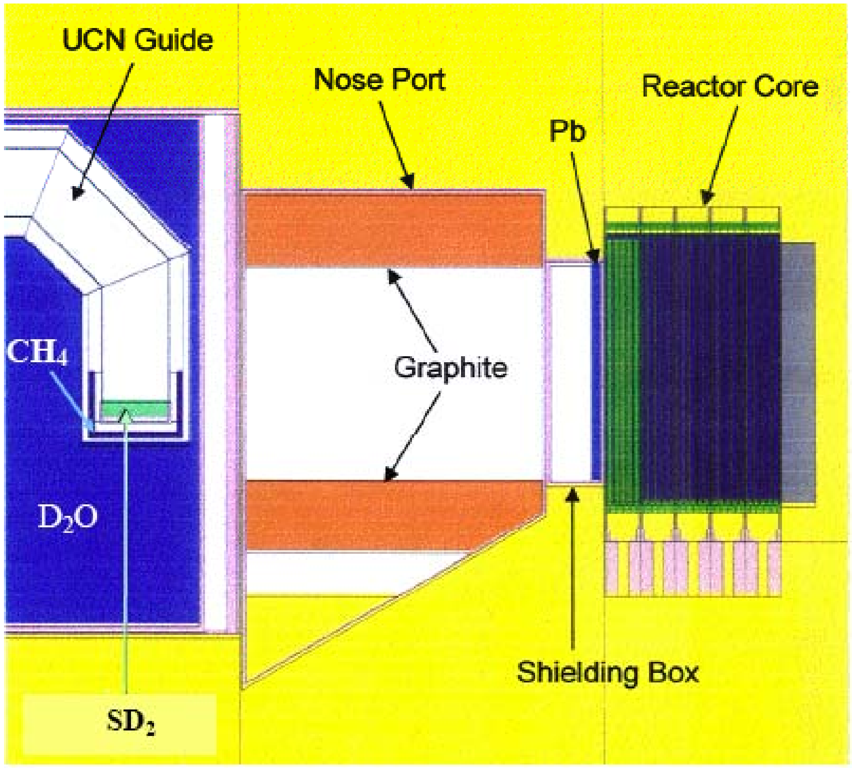
  A. Cook, K. Kincaid, G. Wicks

Local research groups with overlapping interests:

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

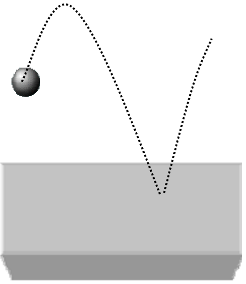


NCSU PULSTAR
Source Schematic

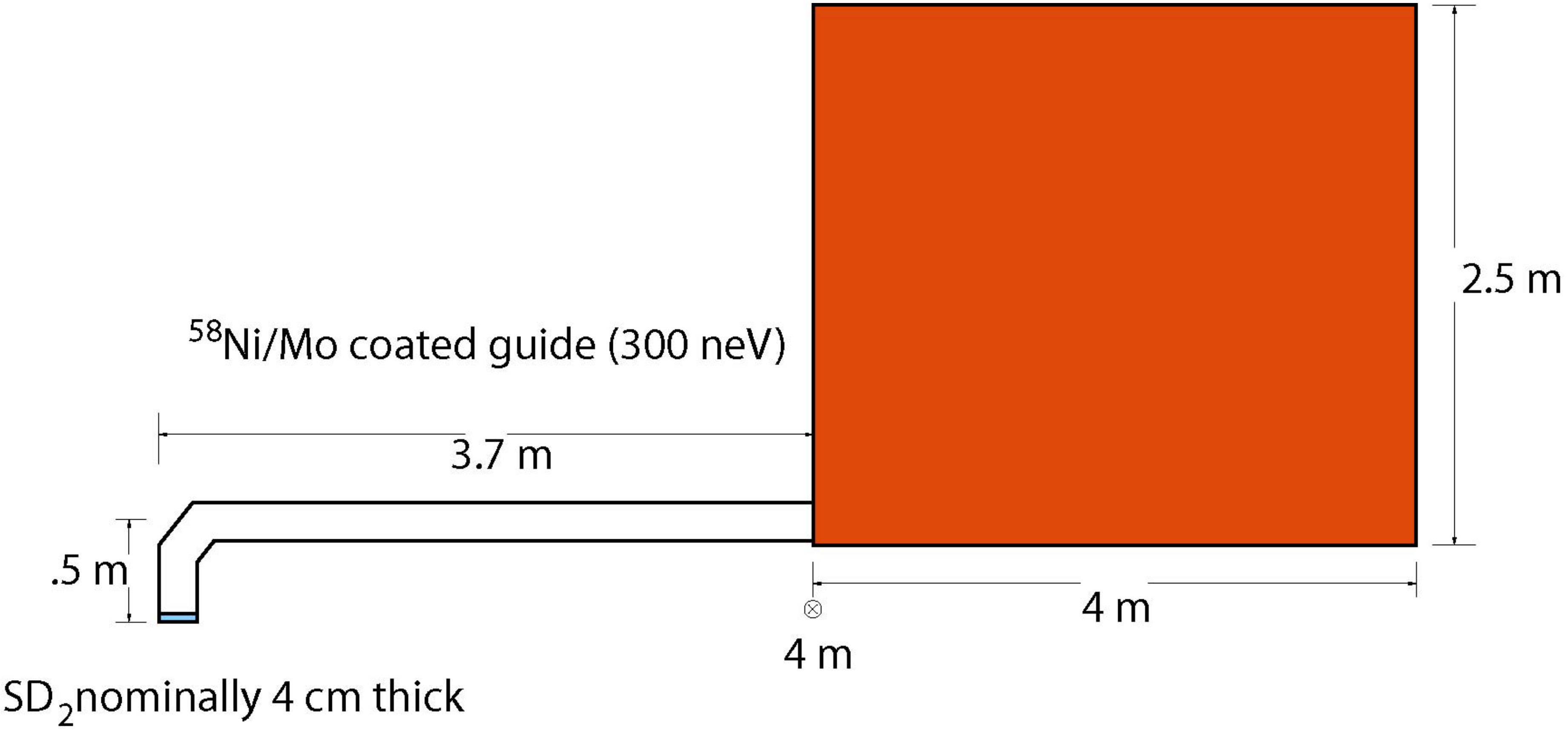


- 1 MW (funding for 2 MW upgr)
- Floodable Helium Nose Port
- Heavy Water Thermal Moderator
- ^{58}Ni-coated guides

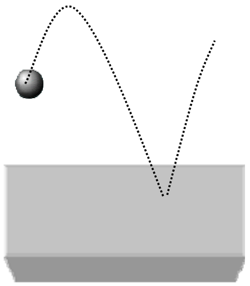
UCN extracted from $SD_2 = 3\times10^6$ UCN/s



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

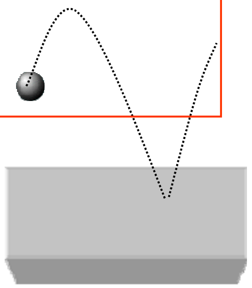
Box loading efficiency: 30%

325s avg. residency in experiment

Best case: diffuse walls, specular floor

discovery potential = 2.3×10^9 Ns

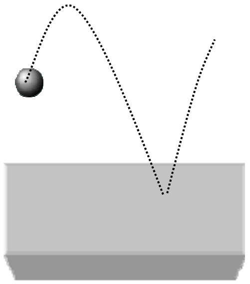
$\tau_{nn} > 1.1 \times 10^8$ s



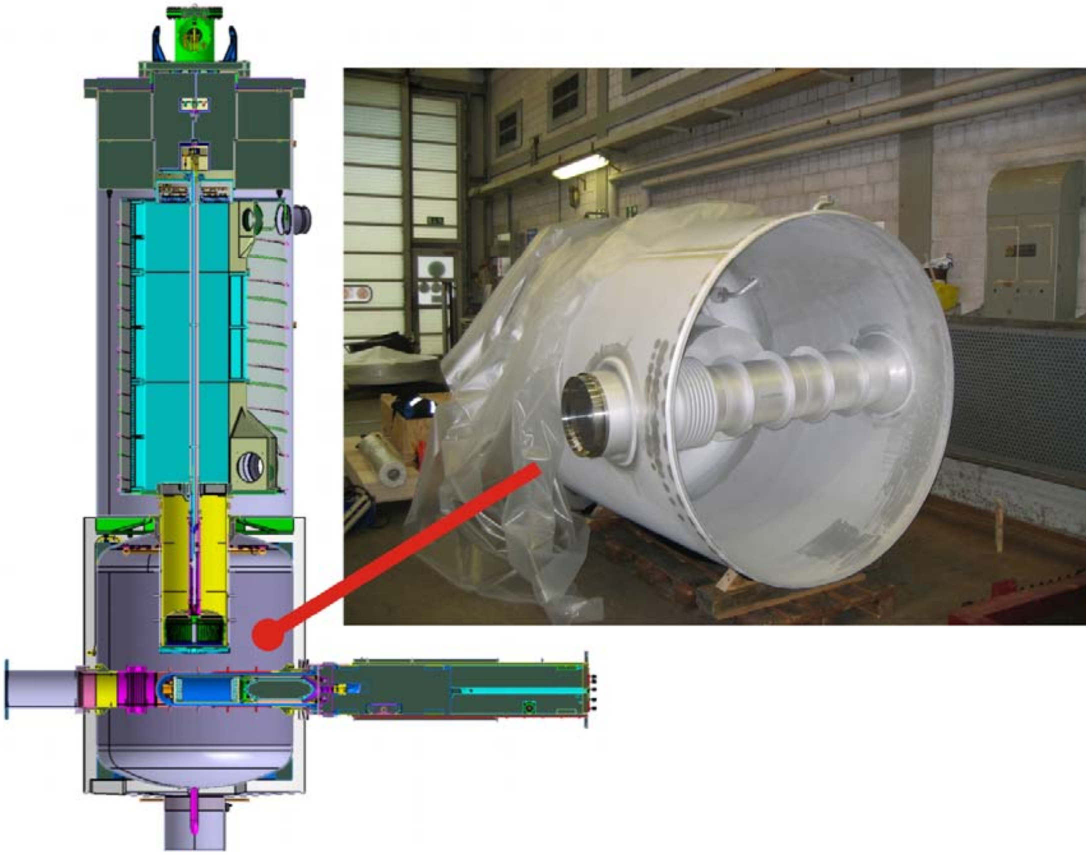
Ultimate Reach with PULSTAR

- “straightforward gains”
  - 4 years of running

    $\tau_{nn} > 2.2 \times 10^8$ 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)
  - Solid nitrogen source (interesting!)
  - Larger vessel (requires modifications to facility)



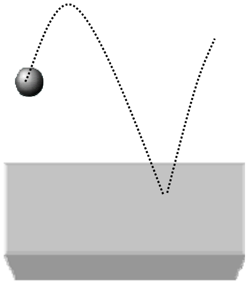
The Solid Deuterium Source at PSI



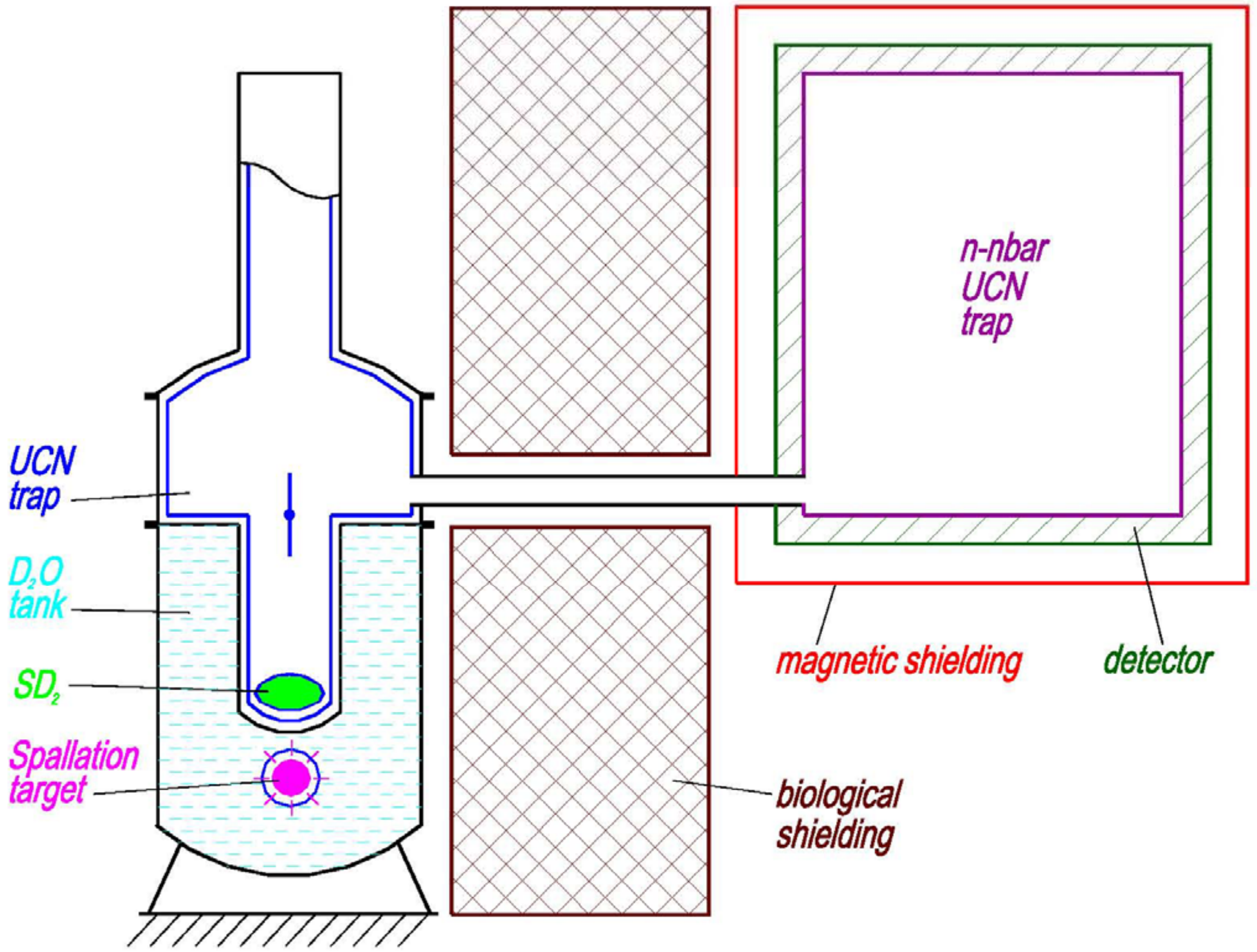
Total beam power 10 kW:
  540 MeV beam
  2mA
  1% duty cycle (8s/800s)

Commissioning runs began Dec. 2010

Limiting densities about 1000 UCN/cm^3

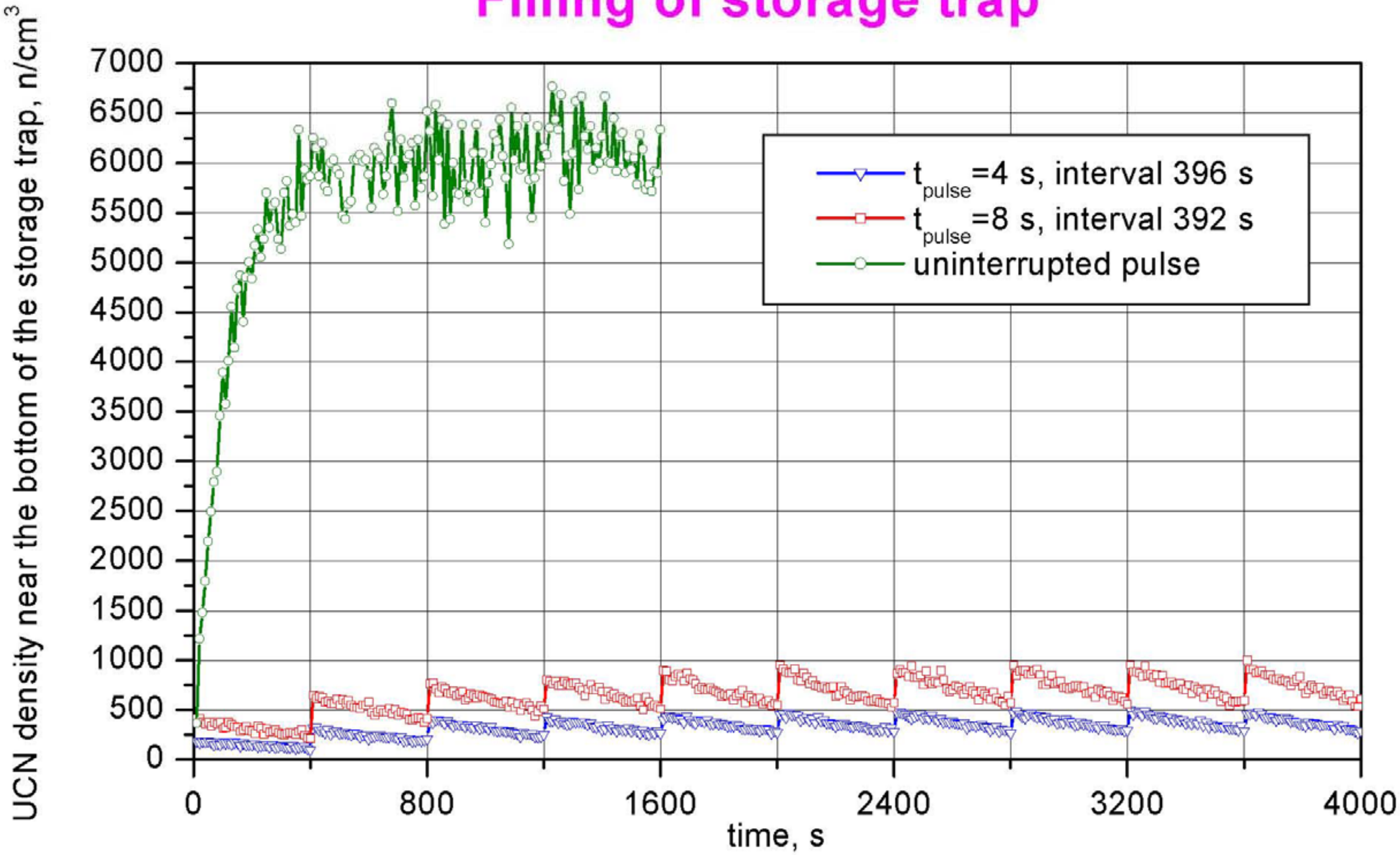


Systematic studies of the PSI UCN source optimized for NNbar by A. Serebrov and V. Fomin



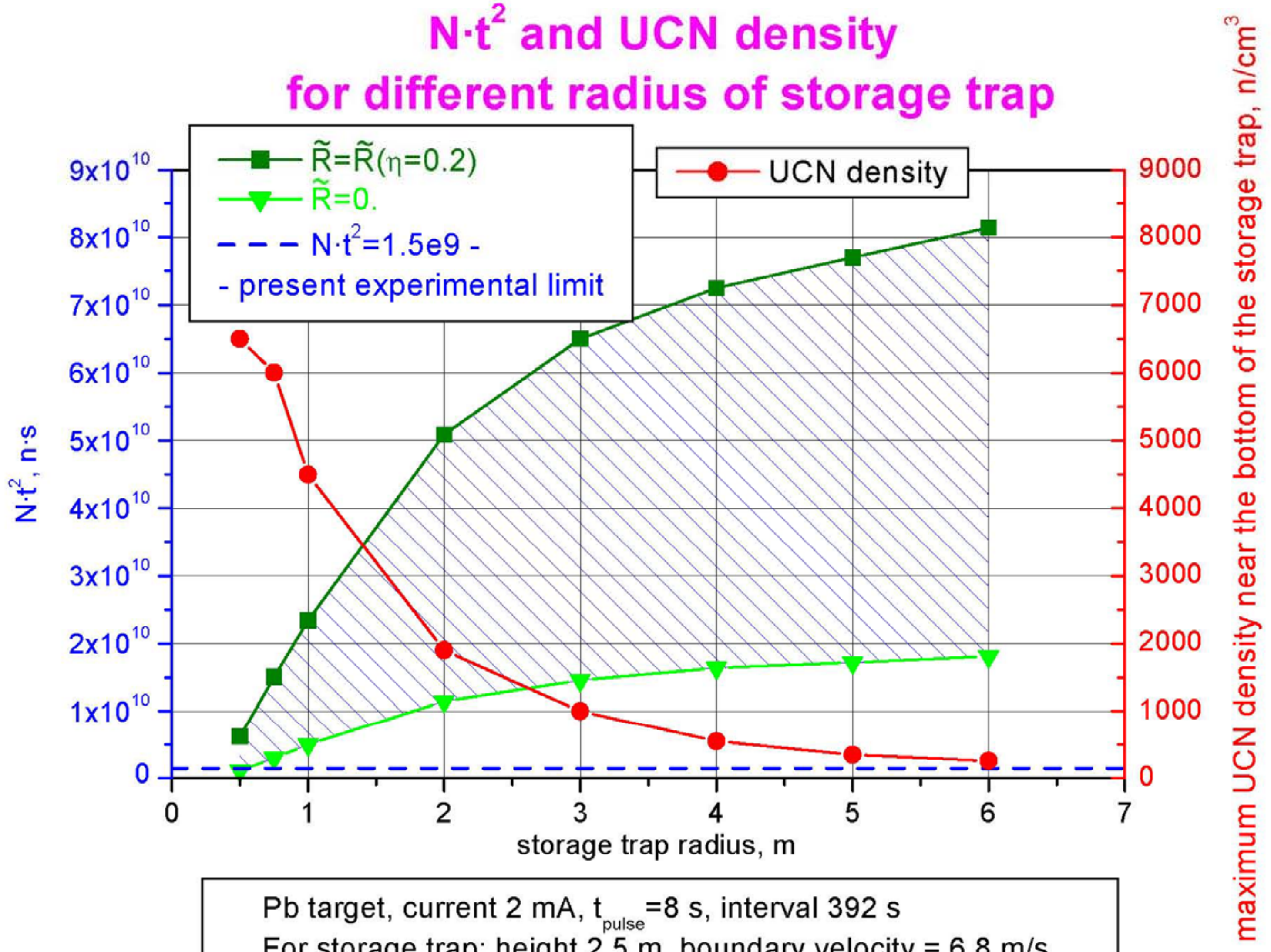
Mode of operation: beam pulsed w/ valve open, then valve closed and UCN stored in system (can, in principle, accumulate)

Filling of storage trap



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

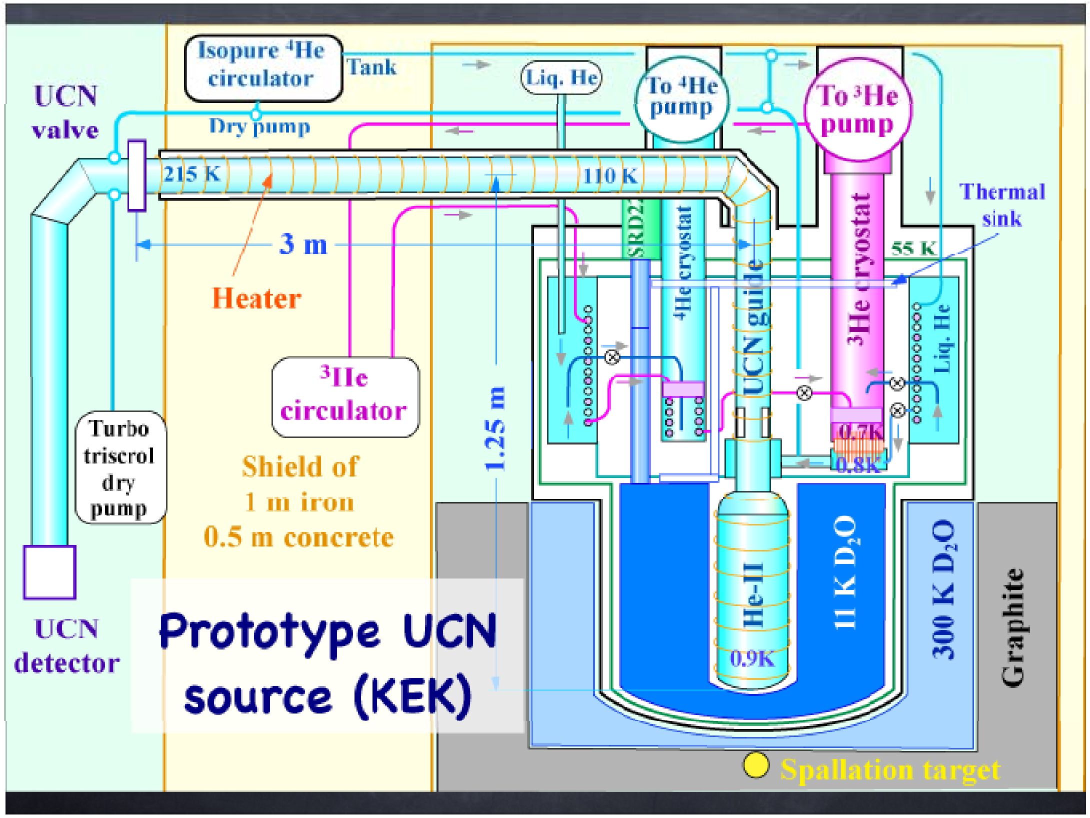
$N \cdot t^2$ and UCN density for different radius of storage trap



Pb target, current 2 mA, t_{pulse}=8 s, interval 392 s
<u>For storage trap:</u> height 2.5 m, boundary velocity = 6.8 m/s,
diffusion 90 %, abs. in walls 3.e-5

Masuda: scaling RCNP He Source

Operating a prototype at the RCNP – basis for TRIUMF source



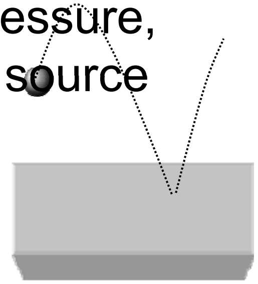
390 W spallation target

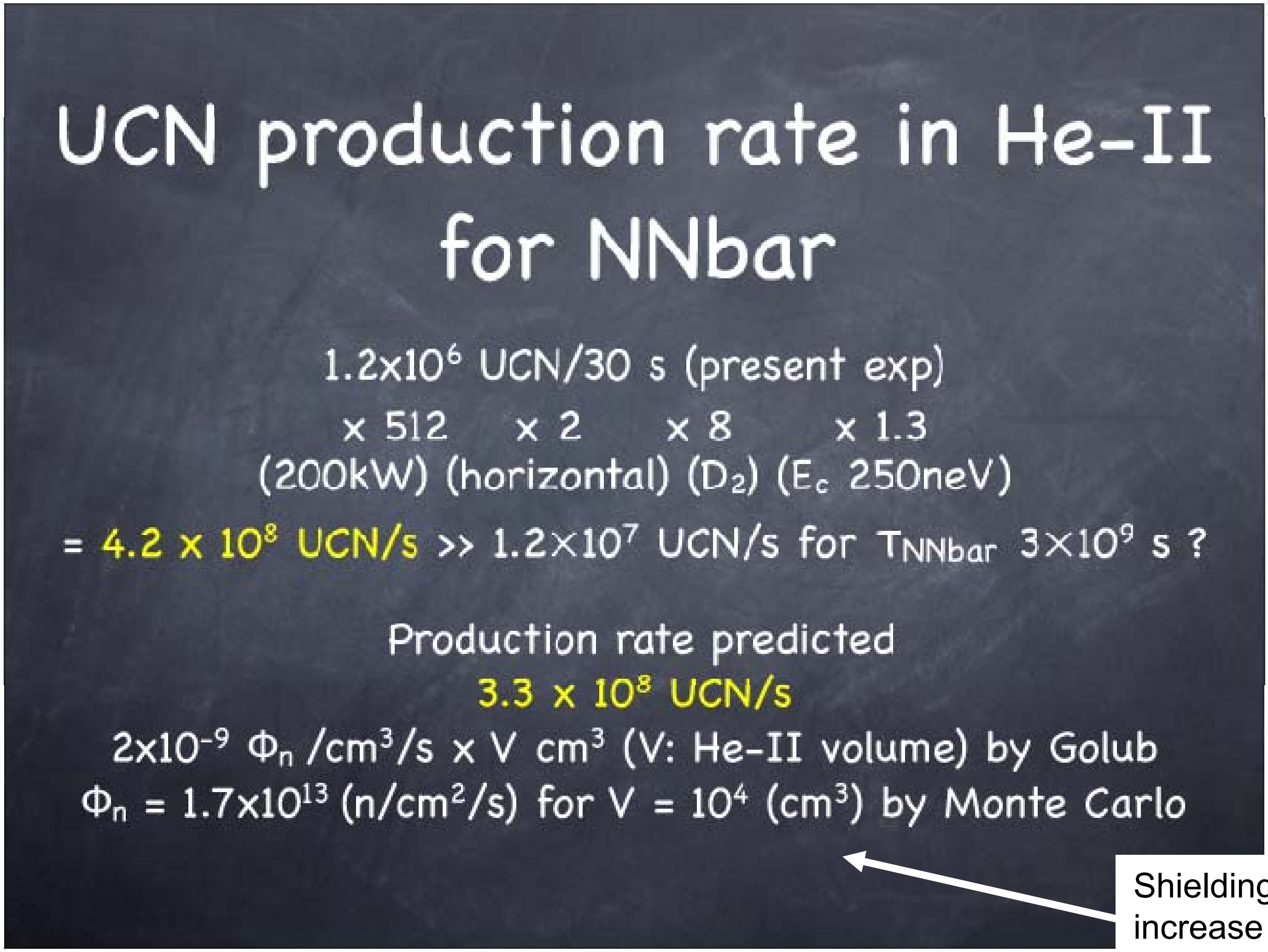
4×10^4 UCN/s

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

$1.2\text{x}10^6$ UCN/30 s (present exp)

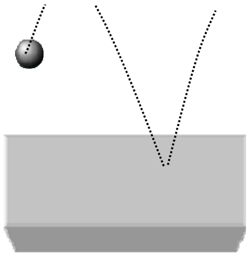
x 512 x 2 x 8 x 1.3
(200kW) (horizontal) (D_2) (E_c 250neV)

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

Production rate predicted
$3.3 \text{ x } 10^8$ UCN/s
$2\text{x}10^{-9}$ Φ_n /cm^3/s x V cm^3 (V: He-II volume) by Golub
$\Phi_n = 1.7\text{x}10^{13}$ (n/cm^2/s) for V = 10^4 (cm^3) by Monte Carlo

Shielding scheme can increase volume

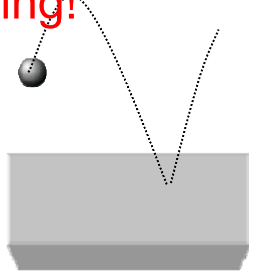
At 200 kW (CW), have 100 W of gamma heating (from MCNP)
- subcooled superfluid He at 1.8-1.9 K in source
- two-phase driven flow to refrigerator/liquifier…
- should be possible!



Comparison (4y expt)

- PULSTAR (1.0 MW): $\tau_{nn} > 1.3x10^{8}$ s
- PULSTAR (3.5 MW), optimized: $\tau_{nn} > 2.2x10^{8}$ s
- SuperK: $\tau_{nn} > 2.7x10^{8}$ s
- FRM II: $\tau_{nn} > 4x10^{8}$ s (perhaps more)
- TRIUMF: $\tau_{nn} > 4.5x10^{8}$ s
- PSI: $\tau_{nn} > 6.1x10^{8}$ s
- 1.9K Superfluid He: $\tau_{nn} > 1.2x10^{9}$ s
- Vertical CN beam: $\tau_{nn} > 3.5x10^{9}$ s

These are very Interesting!



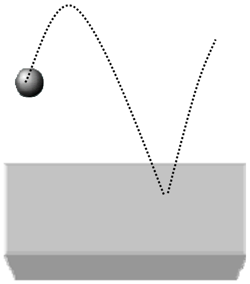
Staged Approach?

(1) Develop UCN experiment:

- Couple 10-20l LHe volume to cold source
- 1.9K, high pressure, superfluid UCN converter with mixed phase coupling to cryogenics
- Modernize detector approach
- Either reactor or spallation target possible

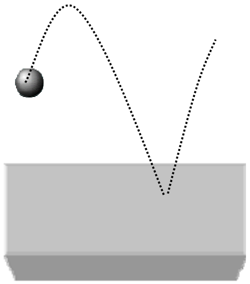
(2) Construct shielded beamline and perform CN experiment

- Keep cold source and detector modules
- Perhaps also keep UCN converter is slower component of neutrons useful (vertical geom)



Creativity?

- For UCN experiment
  - – CPC arrays to increase average flight time
  - – Static fields to produce multi-bounce enhancements
  - – New source materials (^{15}N)
- For CN experiment
  - – Make staged experiment
  - – Use UCN in source for vertical geometry



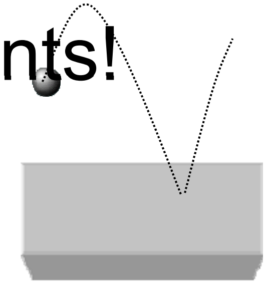
Intensity “frontier” for CN sources ~1 MW

→0.75 MW already demonstrated at the SINQ cold source

100 kW target operated at Los Alamos (LANSCE)

→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!