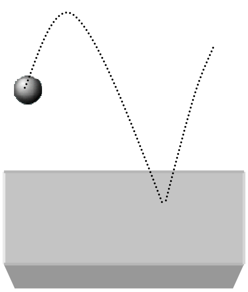
Planned and operating UCN sources in the USA

A. R.Young
NCState University



4/7/2005

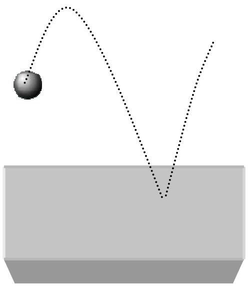
Outline

- Overview of source strategies
- Superfluid He sources coupled to neutron beams: UCN at NIST and the SNS
- The UCNA source program at LANL: SD_2
- The PULSTAR UCN source at NCState

    SD_2

    Superfluid He

    SO_2



Caveat: the limiting densities quoted for these sources are representative, and not intended to be quoted as precise predictions!

Concept of the Superthermal Source

CN population develops due to single scattering processes in the moderator – neutrons don't thermalize in moderator!

10,000+ UCN/cm^3 achievable with SD_2 superthermal sources

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

- Production (at rate R) occurs when a cold neutron (CN) creates a phonon and loses almost **all** its energy
- UCNs accumulate until loss mechanisms (ultimately absorption in SD_2 and neutron β-decay for He) balance production, but ideally upscatter times are **too long** to affect UCN population…

Some 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), also cryogenic constraints less stringent
- Some forms of Carbon might also be very interesting…

Technical Aside on Production

Using SD_2 as a generic example:

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

$$\left(\frac{d^2\sigma}{d\Omega dE'}\right)^{1\ phonon}_{J\to J'} = \frac{k'}{k}\frac{\hbar^2\kappa^2}{2M_{D_2}} e^{-2W(\kappa)} S_{J,J'}(2J'+1)$$

$$\times \sum_n \left(\frac{\hbar\kappa^2}{2M_{D_2}\omega}\right)^n \frac{1}{n!} \sum_{l=|J'-J|}^{J'+J} |A_{nl}|^2 C'^2(JJ'l;00)$$

$$\times \frac{Z(E_{ph})}{E_{ph}} \begin{cases} n(E_{ph})+1 & \text{if } E_{ph} >= 0 \\ n(E_{ph}) & \text{if } E_{ph} < 0, \end{cases}$$

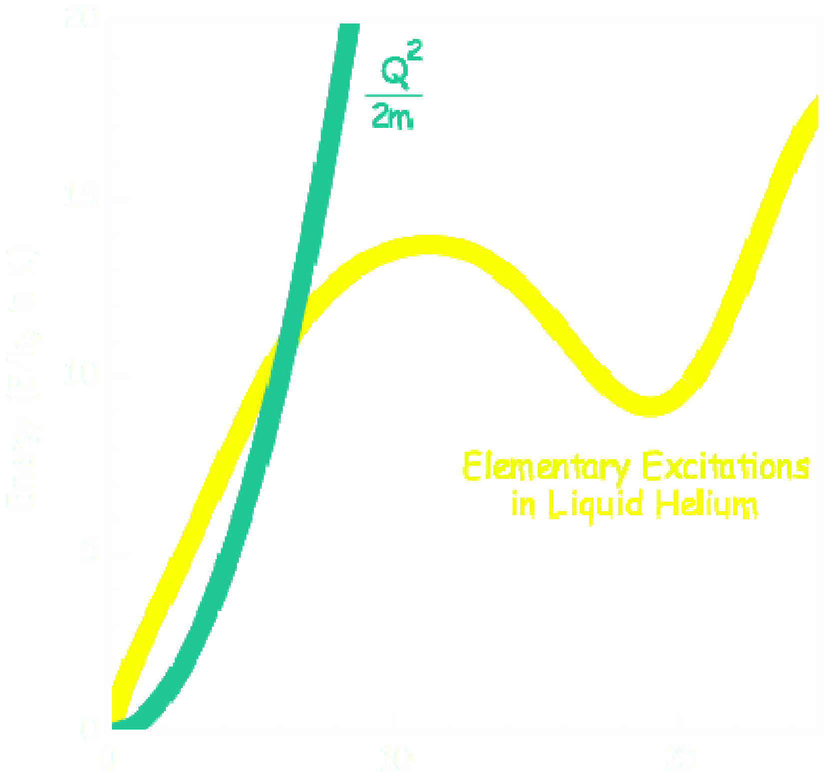
Favors low mass species

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

Existing and planned 8.9Å superfluid He sources

- extremely long UCN survival time, τ, in He

- and because a good fraction of the production "strength" comes from single phonon production with neutron wavelengths very near 8.9 Å



- LHe sources coupled to neutron beams already available at NIST, planned for SNS

Limiting densities

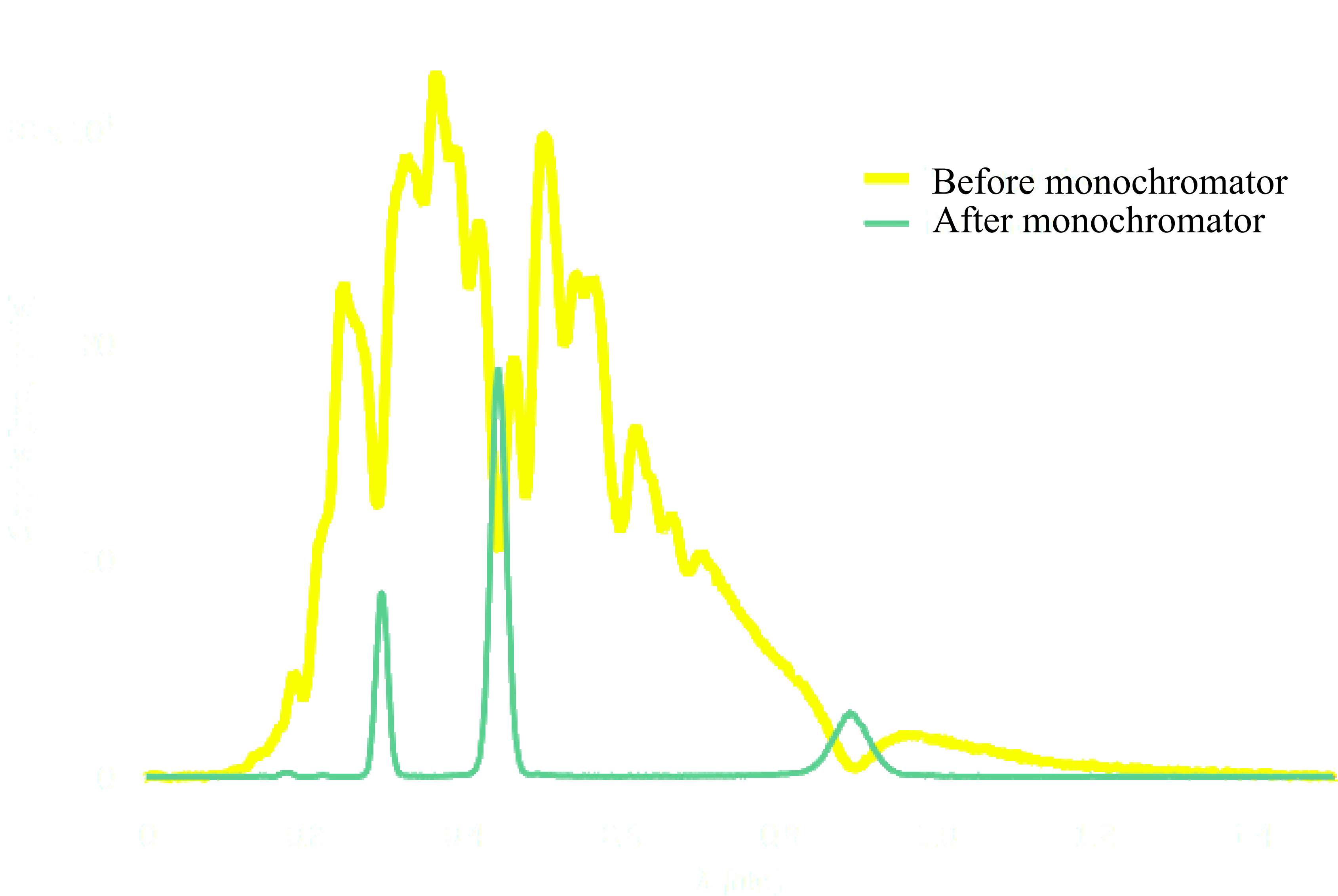
Limiting $\rho = R\tau$

R = production rate

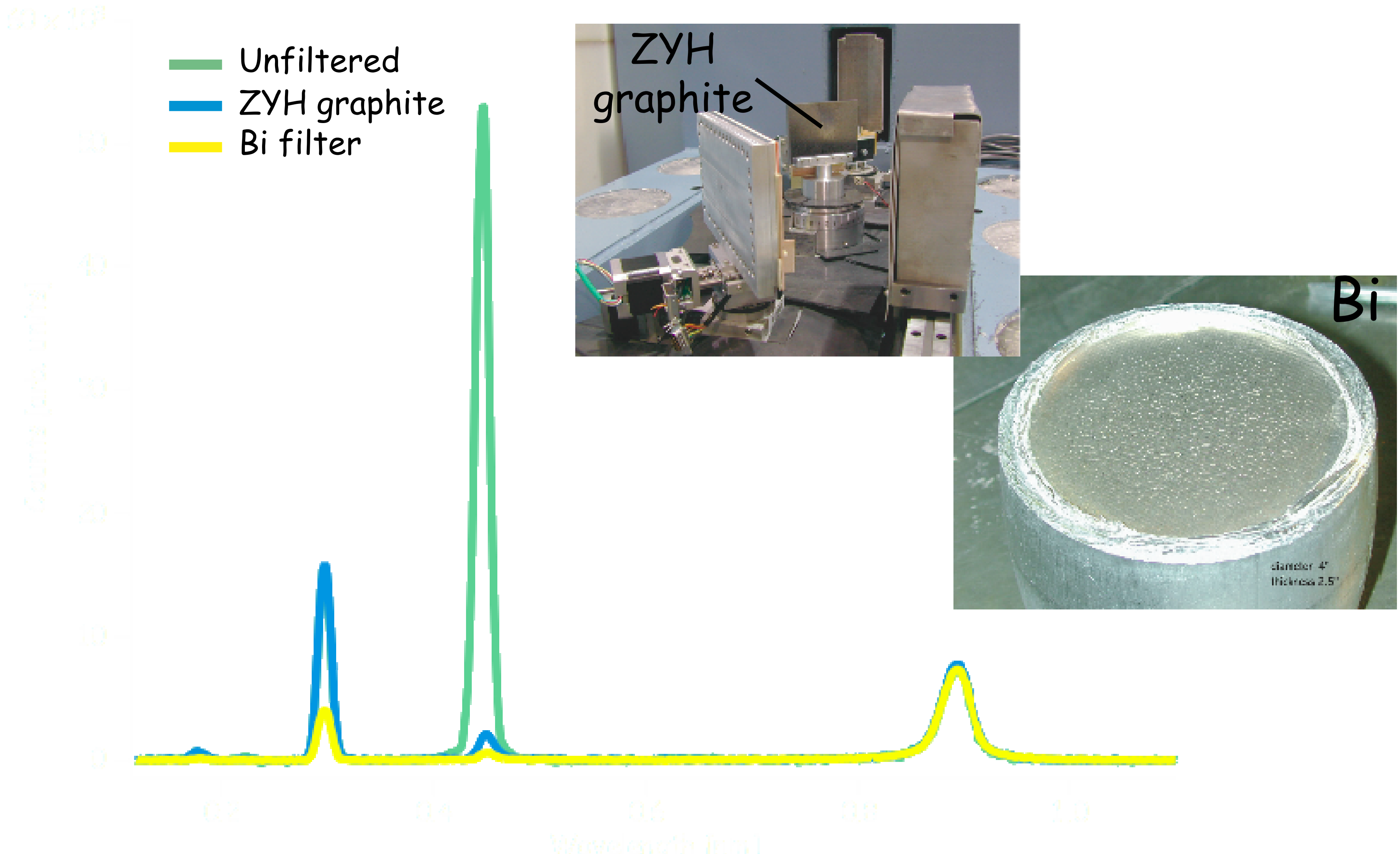
τ = survival time of UCN

- Production rate (in roughly 1 liter) ~ 1/cc/sec at NIST, ~2/cc/sec at SNS
- Limiting densities a few thousand/cc
- Well adapted to storage experiments (lifetime, EDM, …)

Monochromator Spectrum

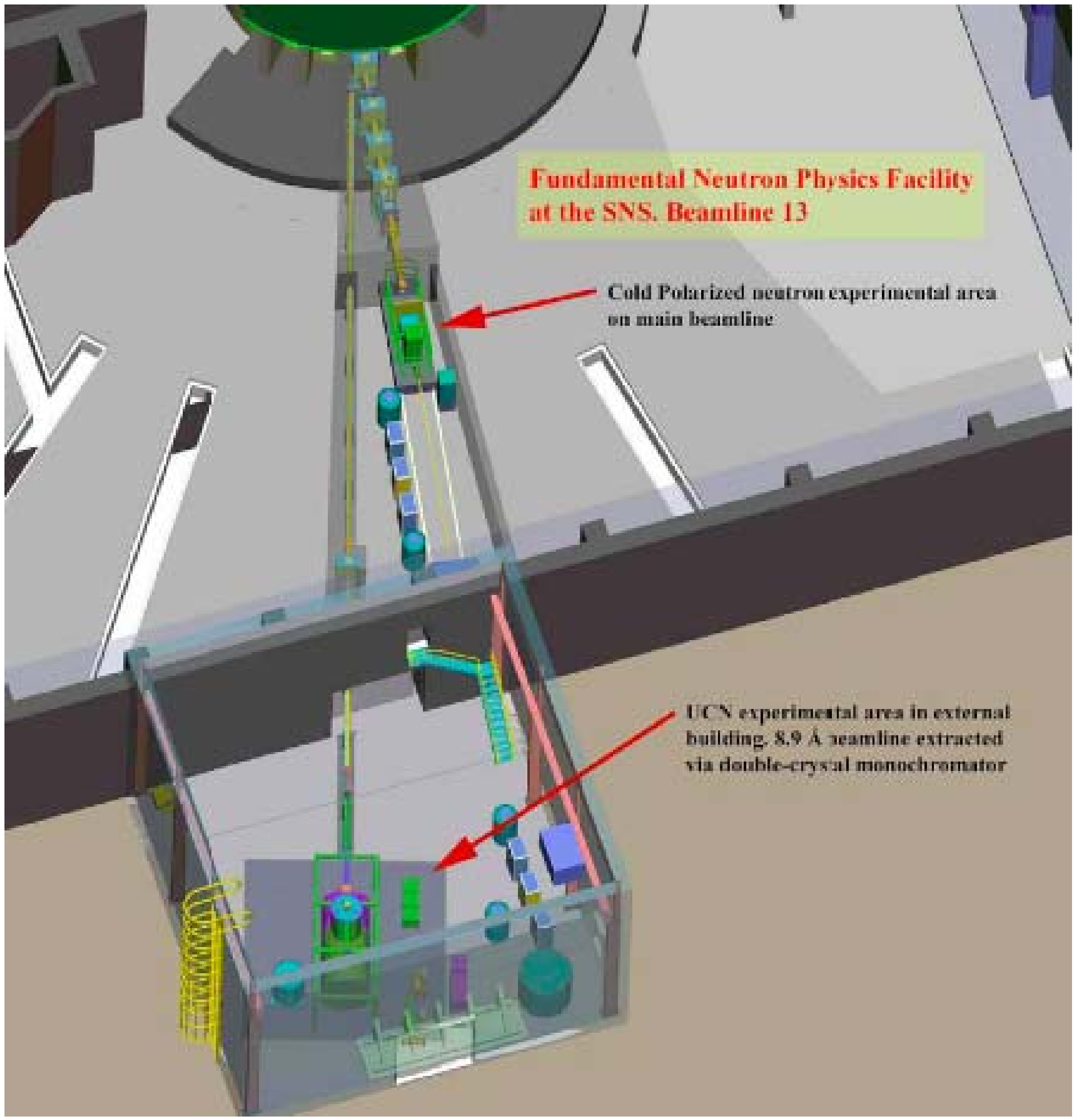


Wavelength Filtering

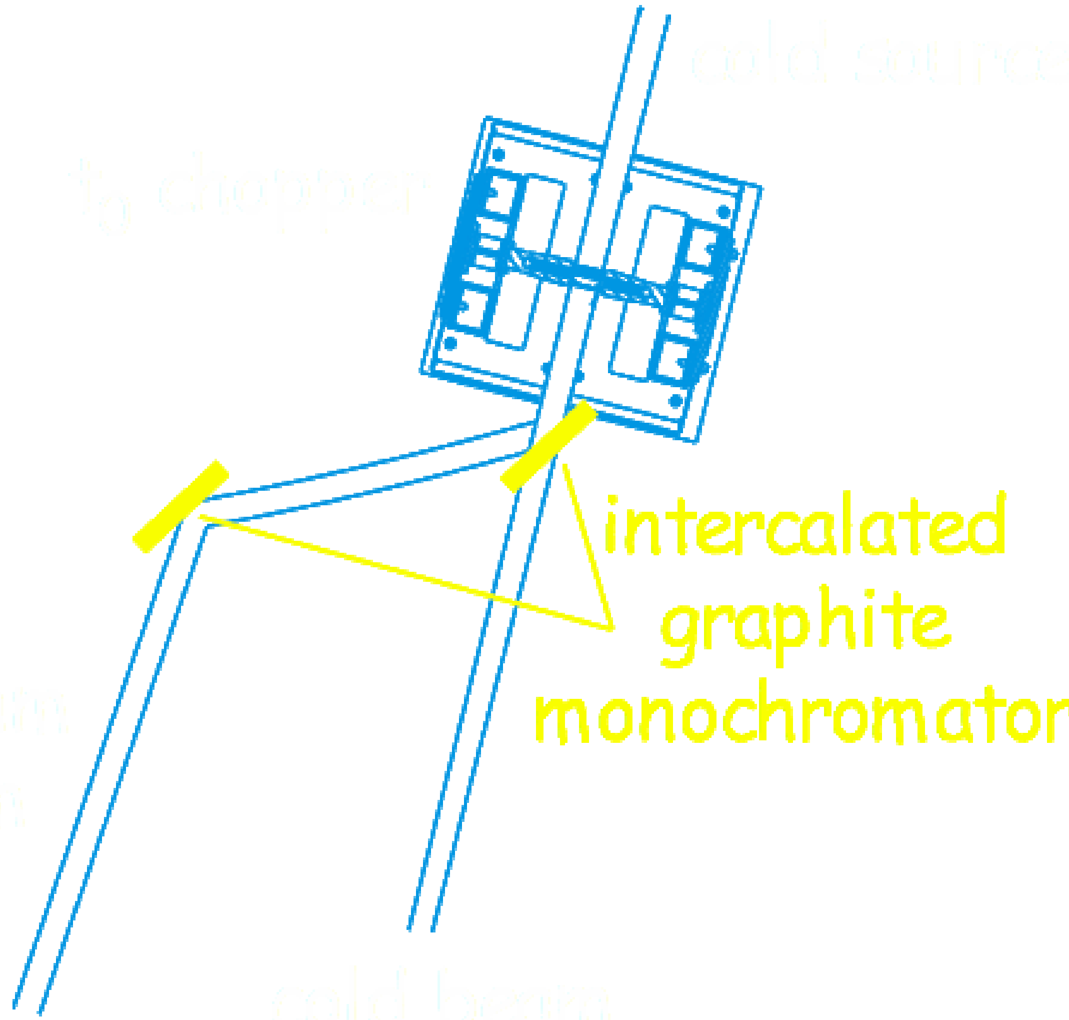


Spallation Neutron Source

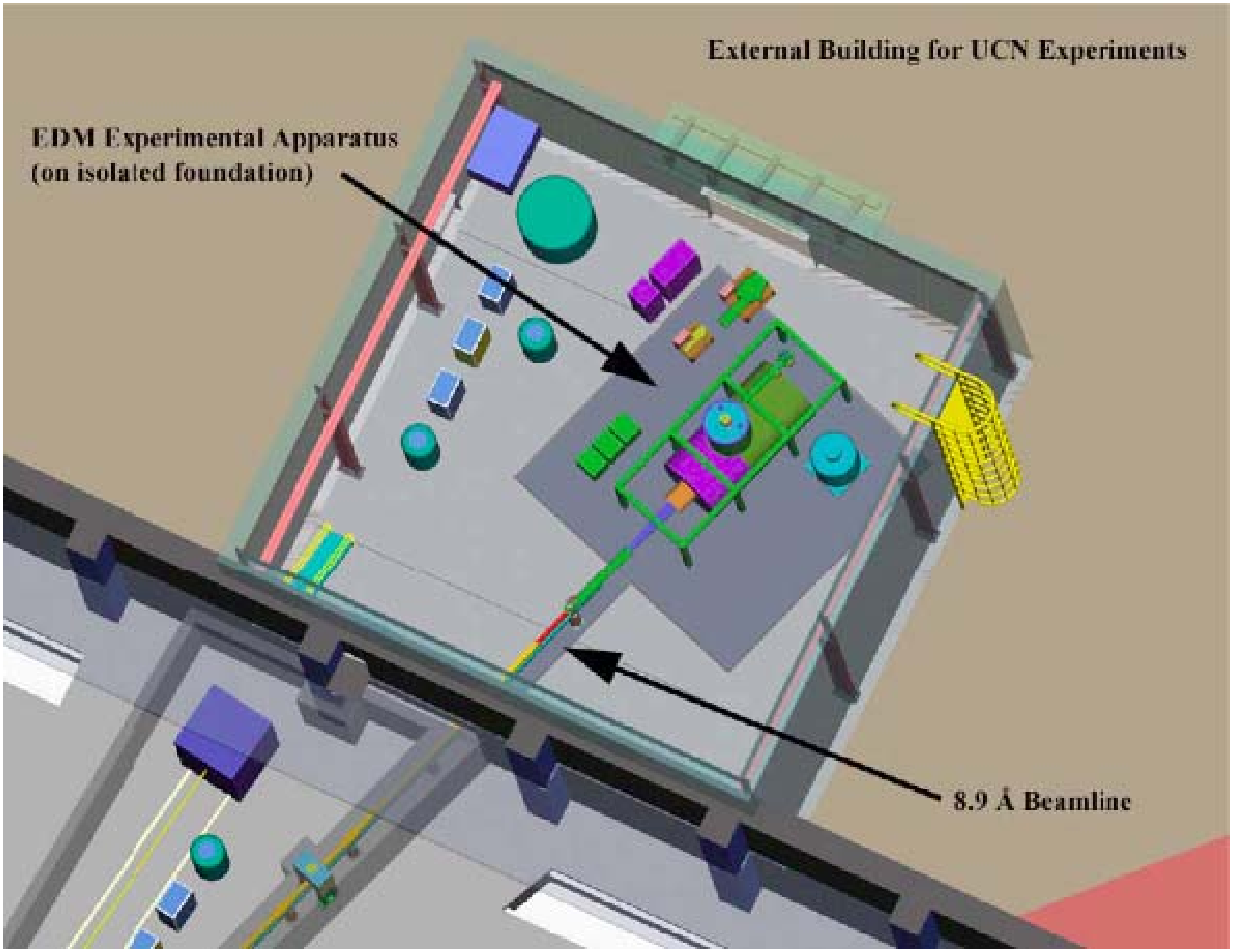
Fundamental Physics Facilities



0.89 nm Beamline

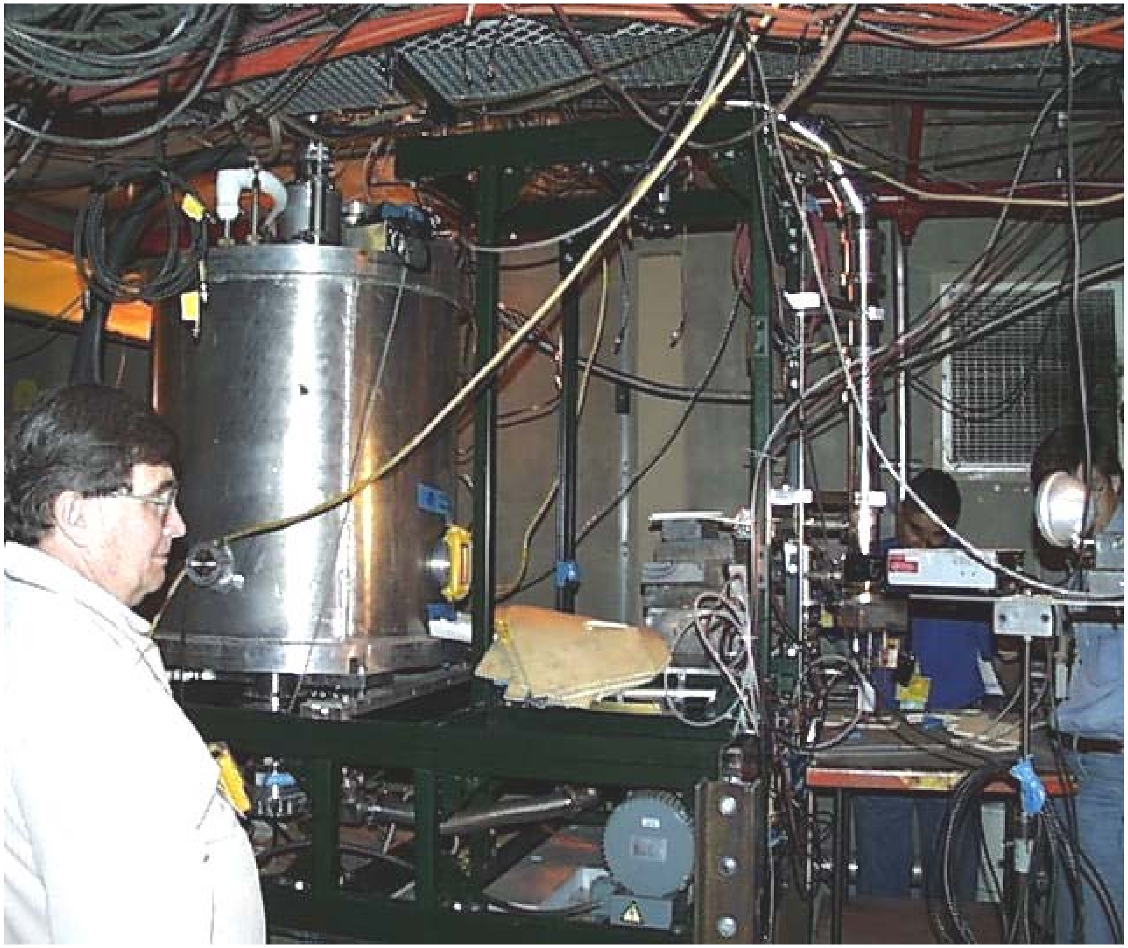


0.89 nm "Outhouse"



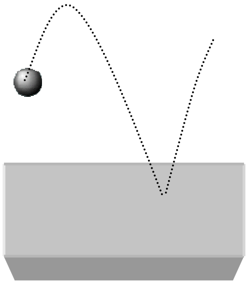
Technical resources and support make this a very interesting place to do physics

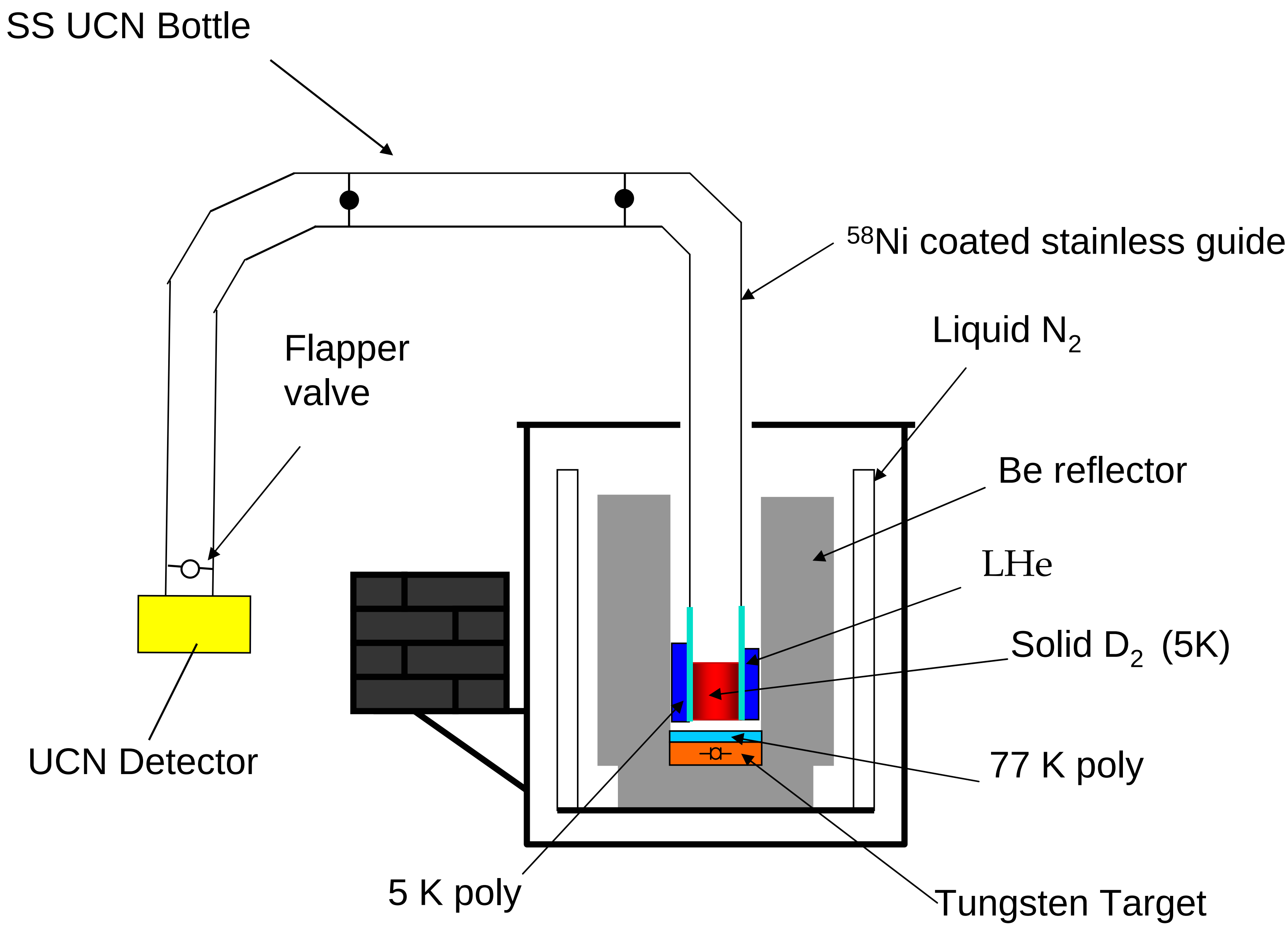
LANL Prototype SD_2 Source Tests



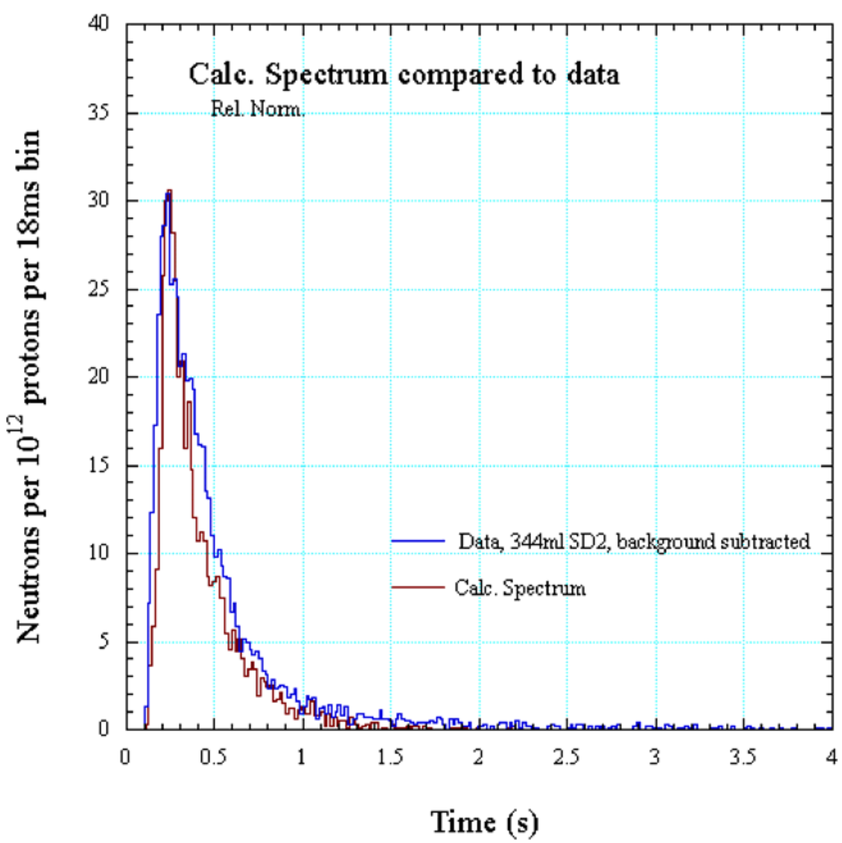
- Source needed for UCNA experiment, with very short (5s) holding time
- Relatively large heat loads from spallation target

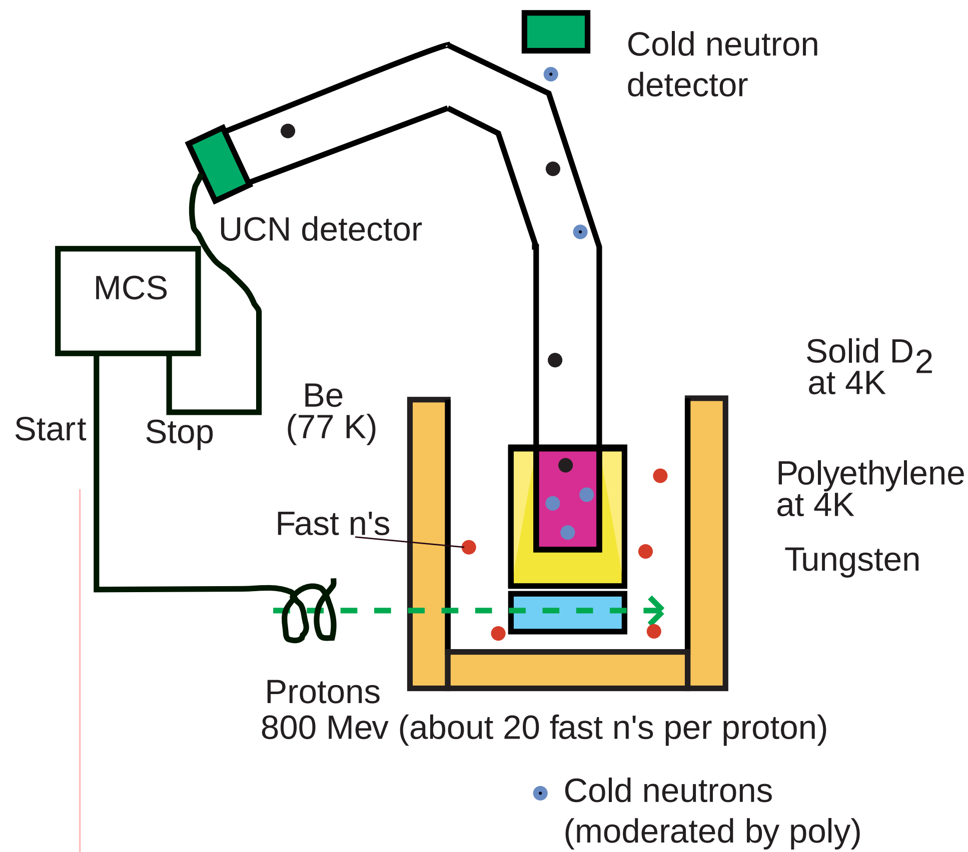
→ high production rates, high (>2 K) T useful → SD_2



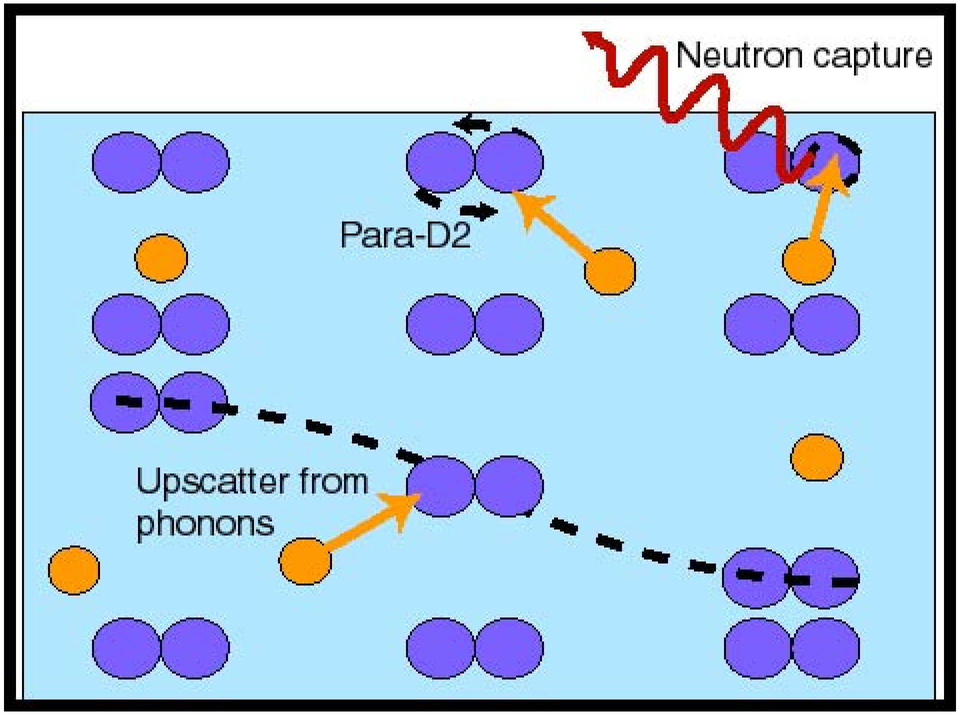

SS UCN Bottle
58Ni coated stainless guide
Liquid N2
Flapper
valve
Be reflector
LHe
Solid D2 (5K)
77 K poly
UCN Detector
5 K poly
Tungsten Target

UCN Production





Lifetime of UCNs in SD_2



Neutron decay (≈ 885 s)

ideal limit Neutron capture on D (or H) (≈150 ms, pure D_2)

Upscatter from phonons present in SD_2 (≈125 ms at 5K)

Spin-flip transitions in para-D_2 (≈1 ms, pure para)

Dominated lifetime in first experiments!

Para-D_2 upscattering

Para: ↑↓   Antisym. Nuclear Spin(S=1) <-> Odd J=1,3,5...

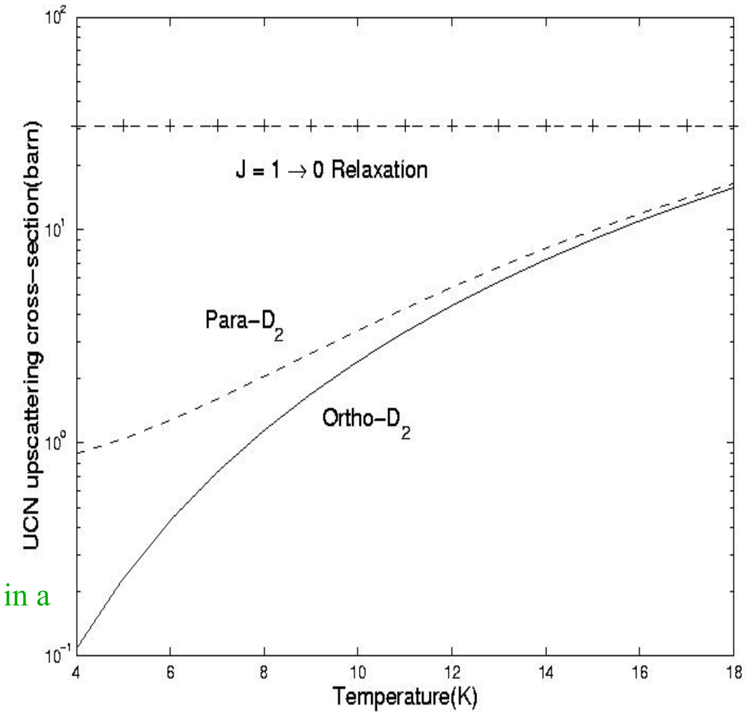
↓ Relaxation rate is small in a non-magnetic environment.

Ortho: ↑↑   Sym. Nuclear Spin(S=0,2) <-> Even J=0(ground state),2,4...

UCN scatter off of para-D_2 with an inelastic upscattering cross section 30 mb without coupling to in the solid. This gives an

$\tau_{up} = 1.5\, m\sec$ **for 100% para-D_2**

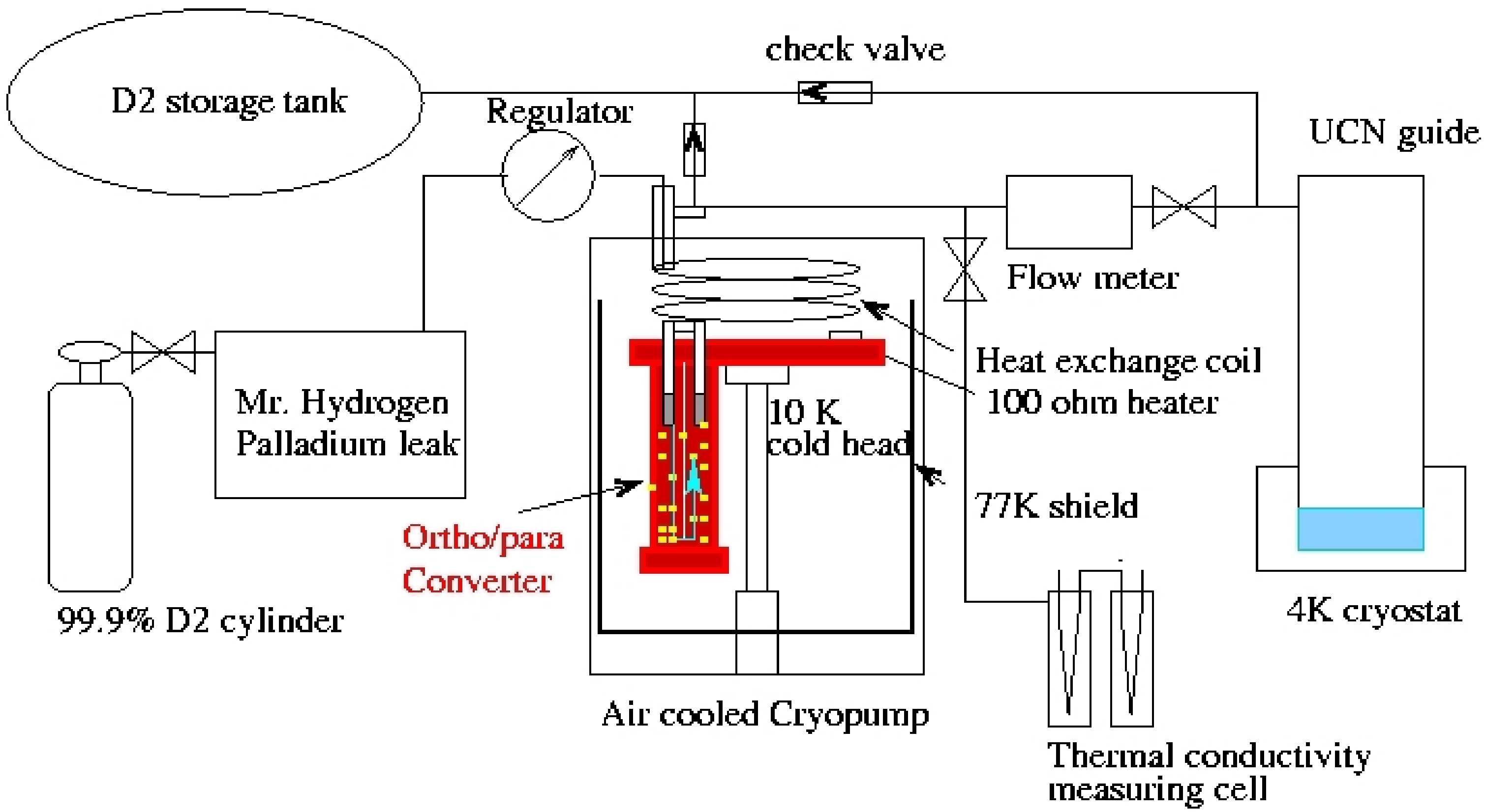
$\tau_{up} = 4.6\, m\sec$ **for 33.3% para-D_2.**



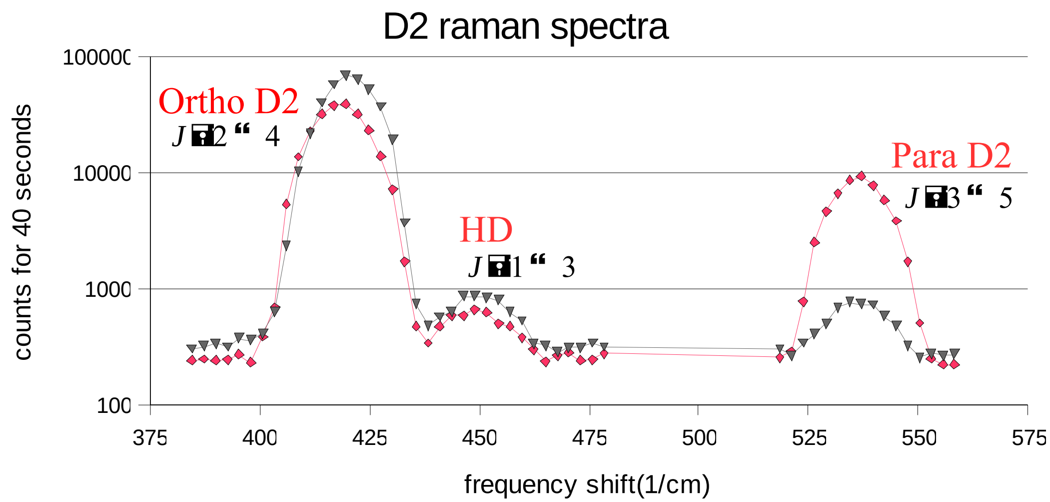
Ref: C.-Y. Liu, A.R. Young and S. K. Lamoreaux, `UCN upscattering rates in a molecular deuterium lattice', accepted by PRB, April 2000.

Deuterium gas handling system

- Use a palladium leak to purify deuterium gas.
- Temperature controlled cryogenic ortho/para converter to convert D_2 to near 99% ortho ground state.
- Flow rate control and monitor.

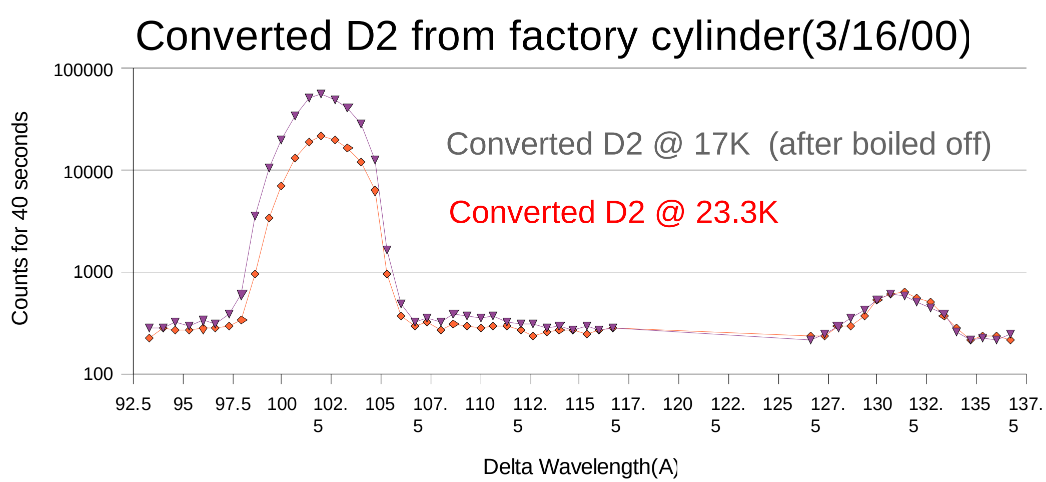


Raman spectrum



With 95% confidence

- Para-D2:
  1.54% +- 0.21%
- HD:
  1.27% +- 0.12%

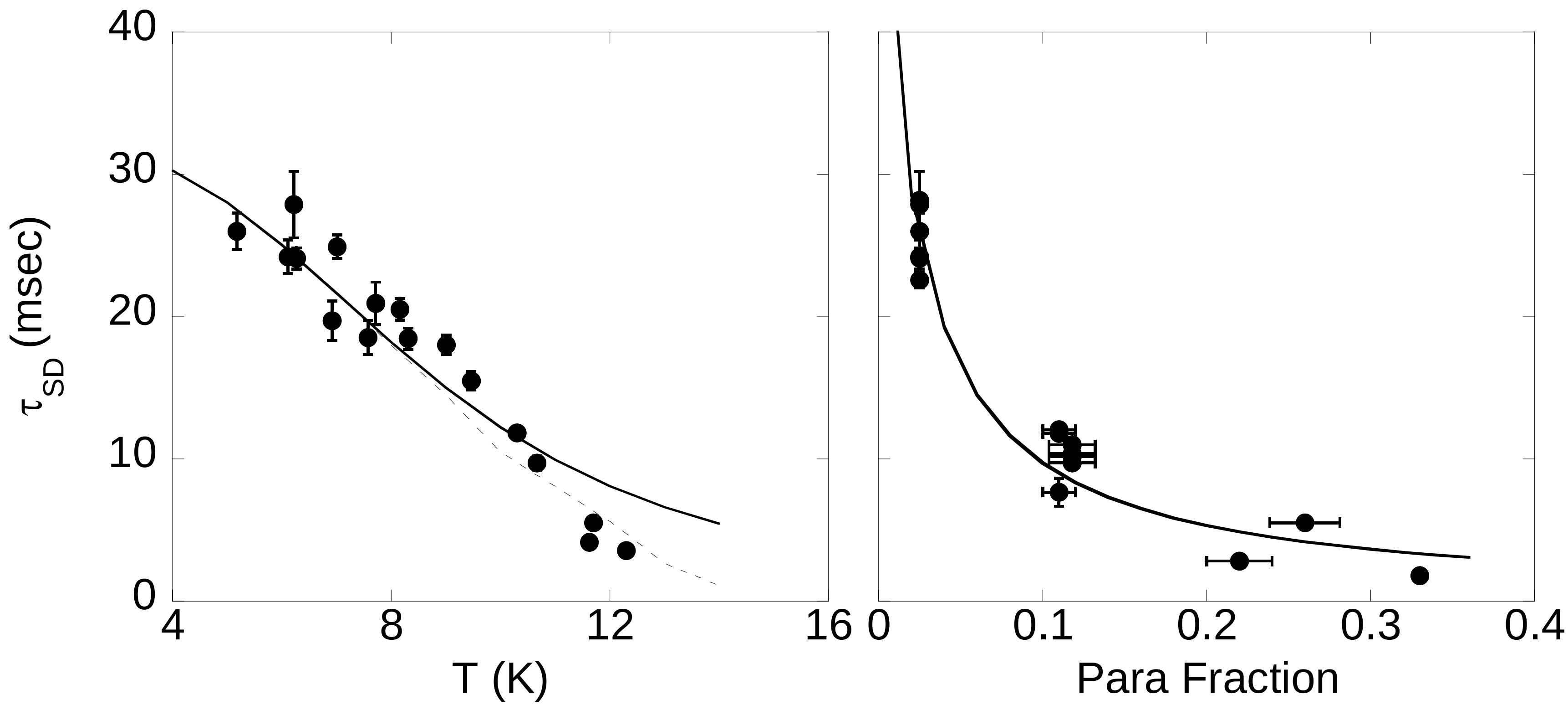


- Para-D2:
  3.44% +- 0.5% (@23.3K)
  1.42% +- 0.2% (@17K)
- HD:
  0.26% +- 0.06%

C.-Y. Liu *et al.*, Nucl. Instr. and Meth. A **508**, 257 (2003).

Prototype Source Key Results

Measured for the first time: UCN lifetime in SD_2

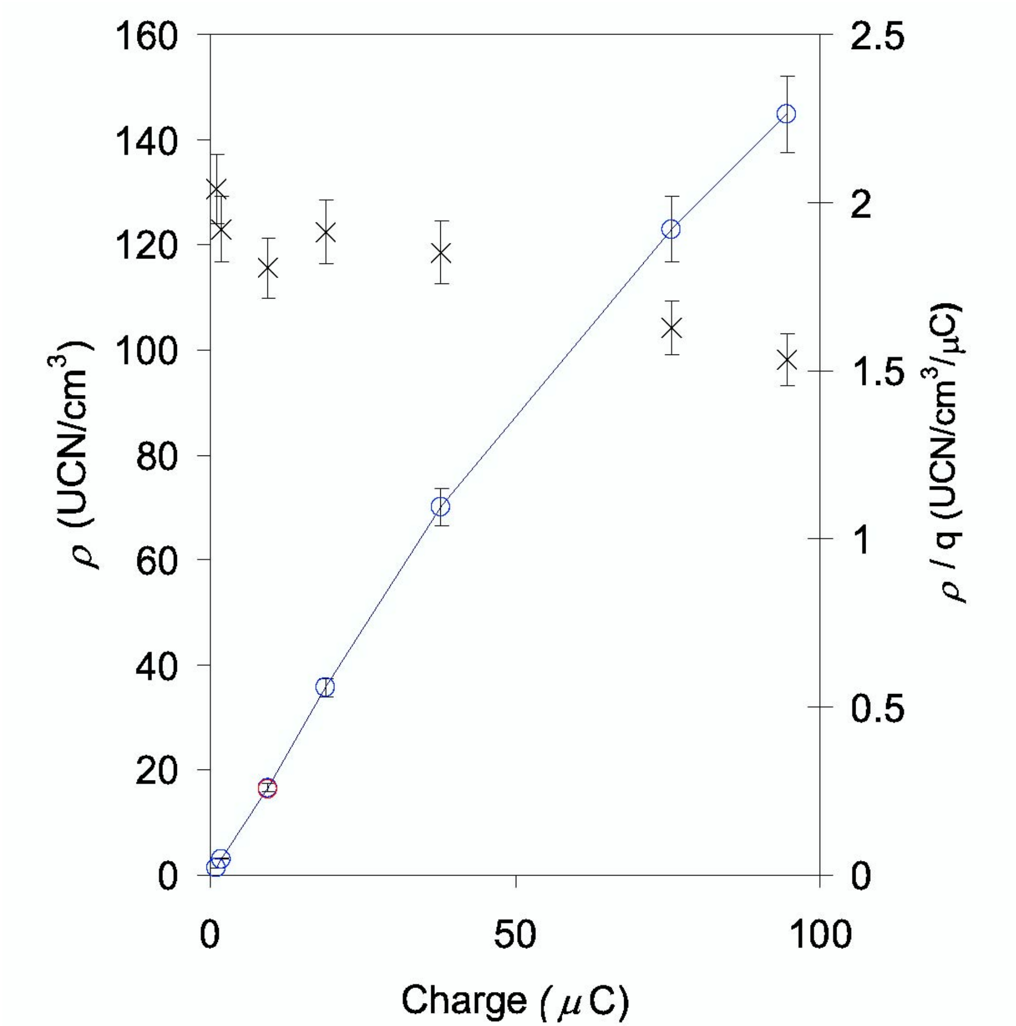


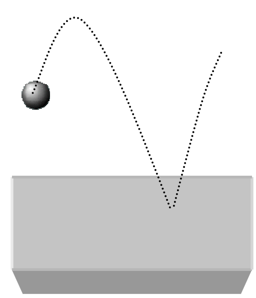
τ_{para} = 1.2 ± .14 (stat) ± .20 (syst)

PhD Thesis: Chen-Yu Liu

C. L. Morris *et al.*, PRL **89**, 272501 (2002).

Very high densities achieved





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

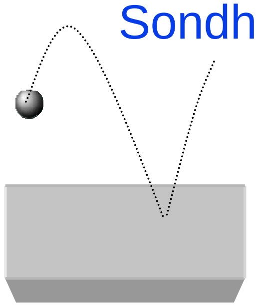
A. Saunders *et al.*, Phys. Lett. B **598**, 55 (2004).

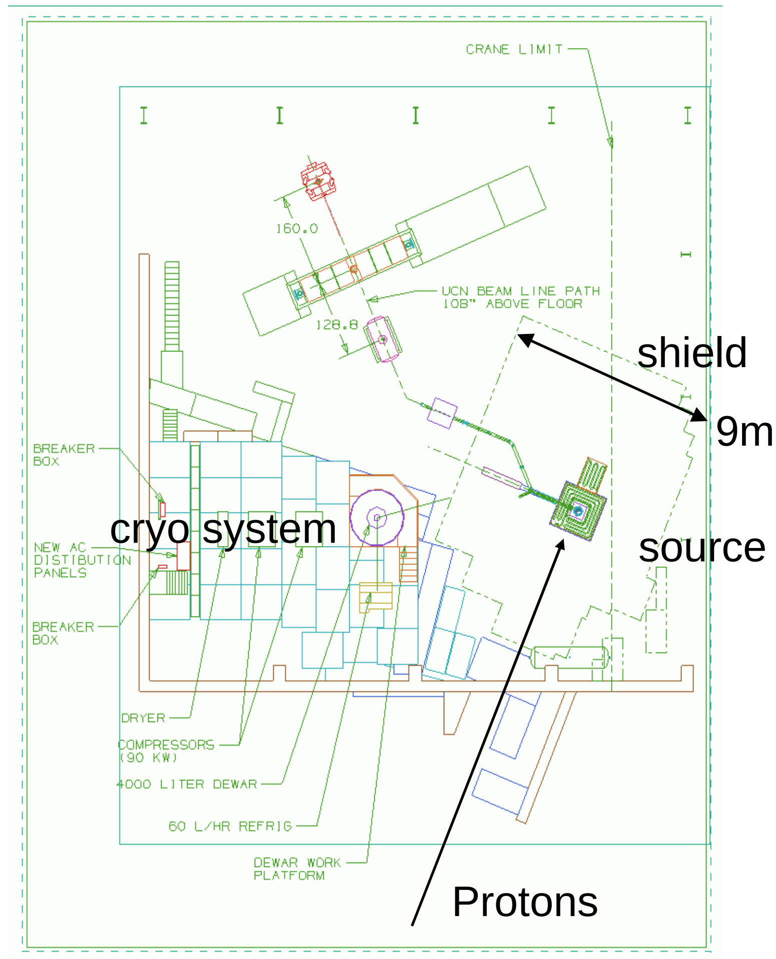
New Source and Experiment in Area B

A new, full scale UCN source supplying UCN to a beta-decay experiment in Area B

New Beam Line
New Shield Package
New Cryogenic Deuterium-based Source
Refurbished MEGA cryo system

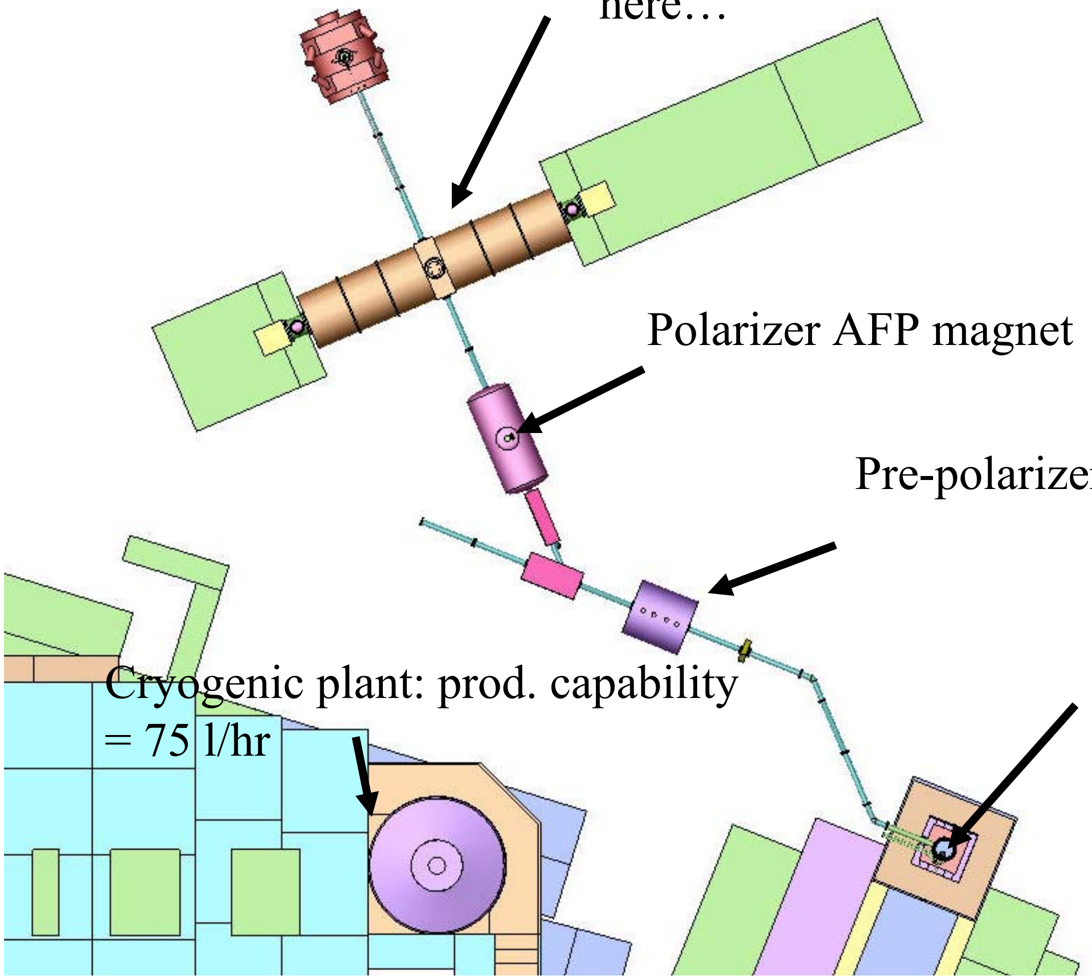
Design team: J. Boissevain, L. Marek, C. Morris, J. Novak, A. Saunders, W. Sondheim, B. Teasdale, J. Waynert





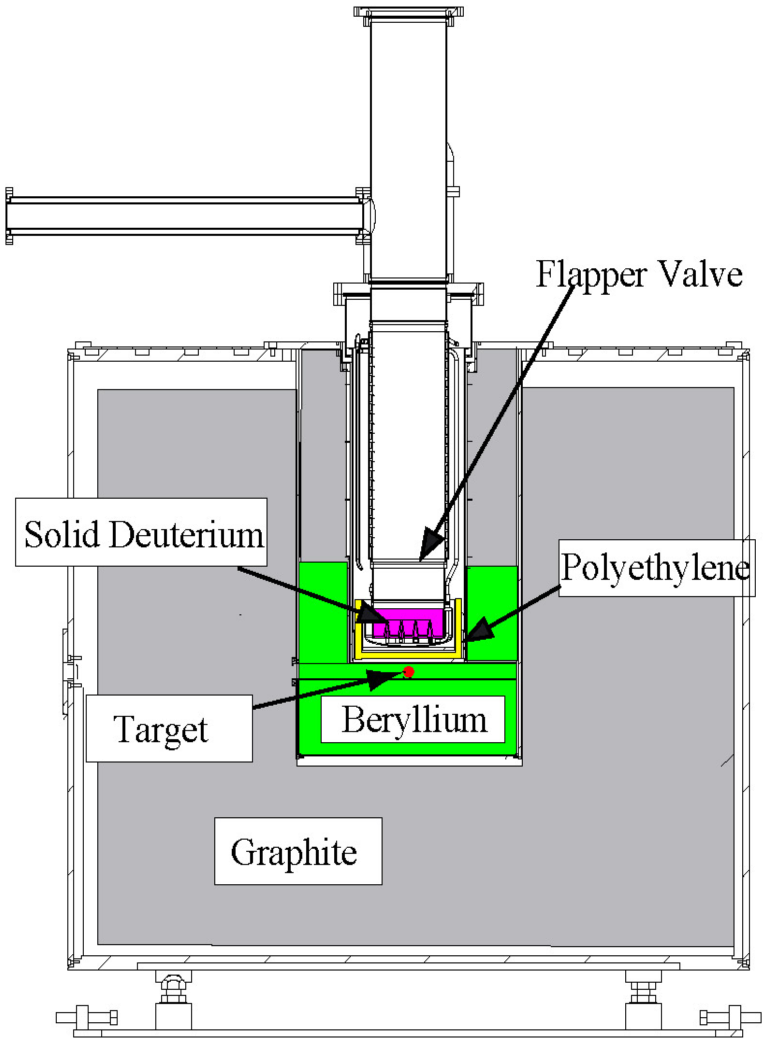
Up to 100 μA of 800 MeV protons available

Source feeds UCNA experiment at the end of 15 m of guide (holding time 5 s…need high prod. rates!):

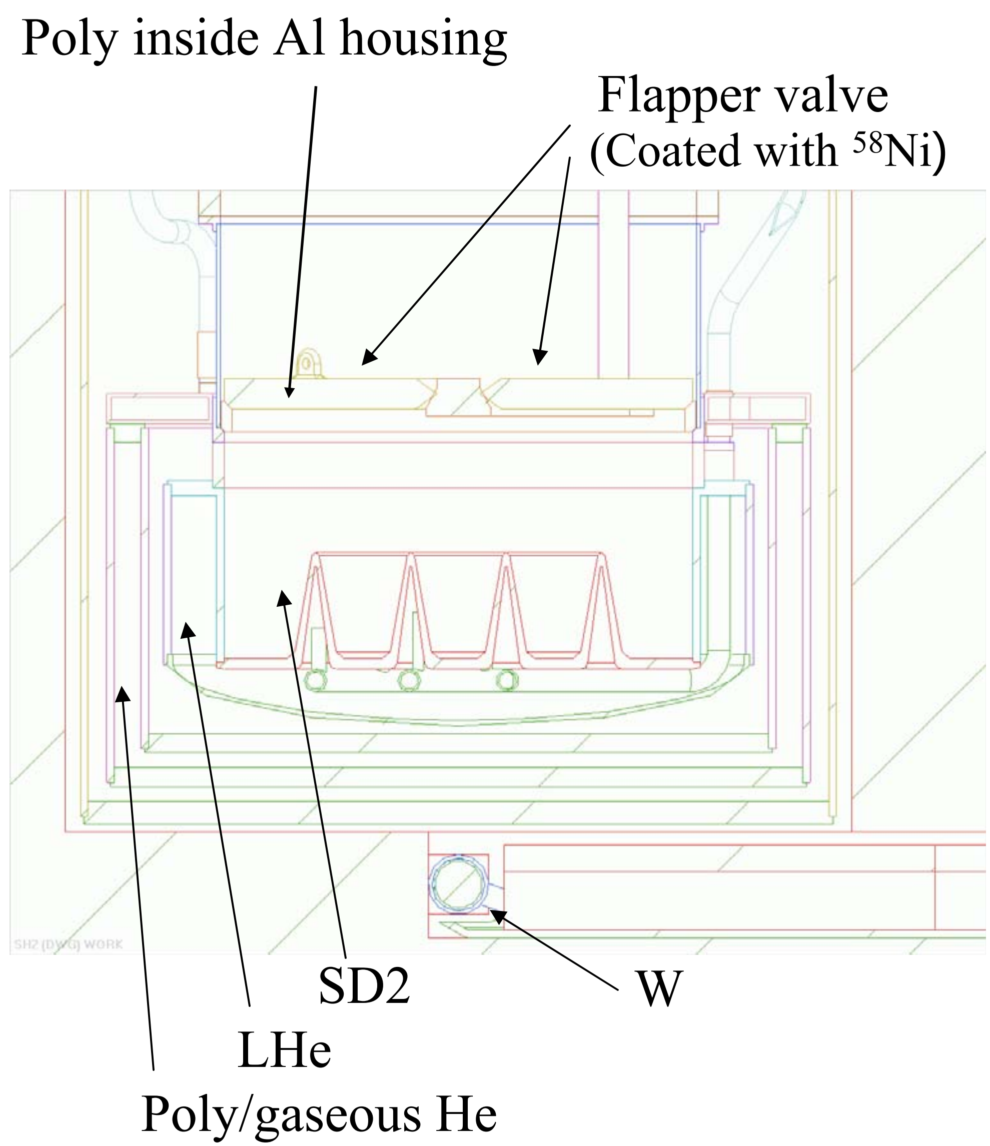


Cold Section of Cryogenic Insert

Max. cooling power at 4K: ~75W (100 liter/hr LHe)



Thermal conductivity of SD_2 limits acceptible beam currents….



UCN Production and Heat Loads

Current plan: 4μA average, 800 MeV proton beam (1 macro pulse every 10 sec)

Current engineering limit: > 10 μA

- Total UCN produced ~750/cm³ μA (flapper open during pulse)

  per pulse

  1liter SD_2 – 30 million UCN/pulse

- Be and W 440 W/μA
- Poly 3.5 W/μA
- LHe resevoir and cryostat 2.1 W/μA
- SD_2 1.3 W/μA

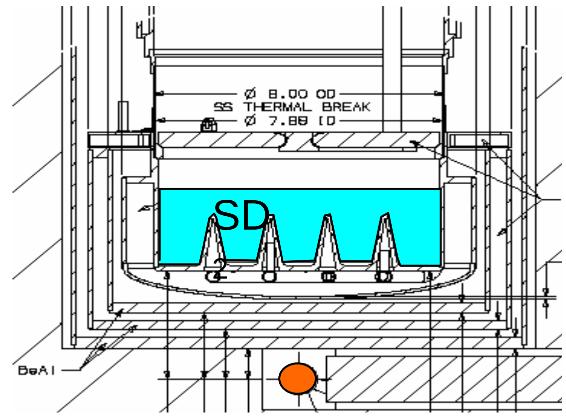
Total SD_2 heat load 5.2 W at 4 μA

Target density in UCNA decay volume > 30/cm³

(more than order of magnitude greater in source storage volume)

Source Performance Tests: invaluable feedback towards constructing a working production SD_2 source

- Source tests performed after a first pass at optimizing proton beam tuning and flapper timing
- Measured UCN production/pulse
- Measured time profile of UCN production (related to source lifetime)



Results:

- Source production down **because of known compromises** in construction
- Time-of-arrival curves roughly consistent with simulated source

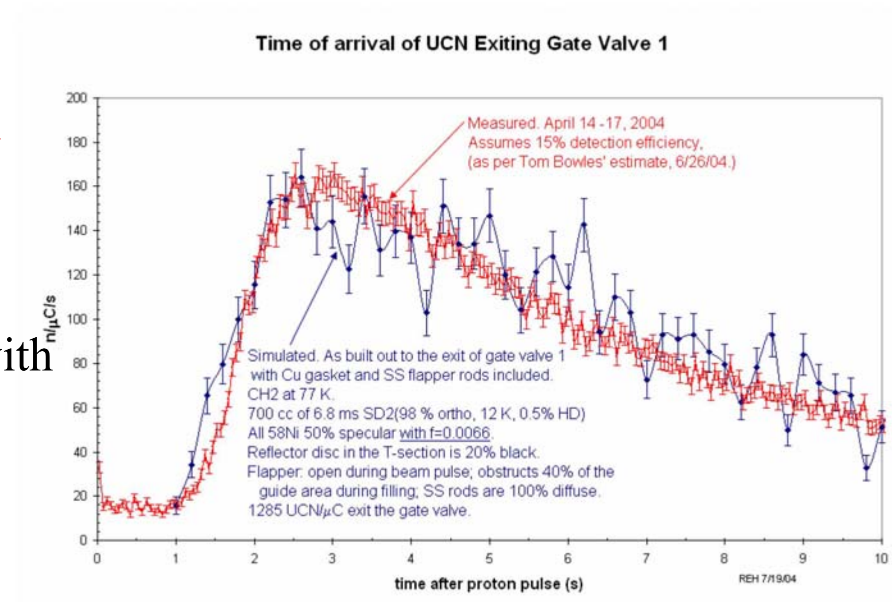


Figure 7

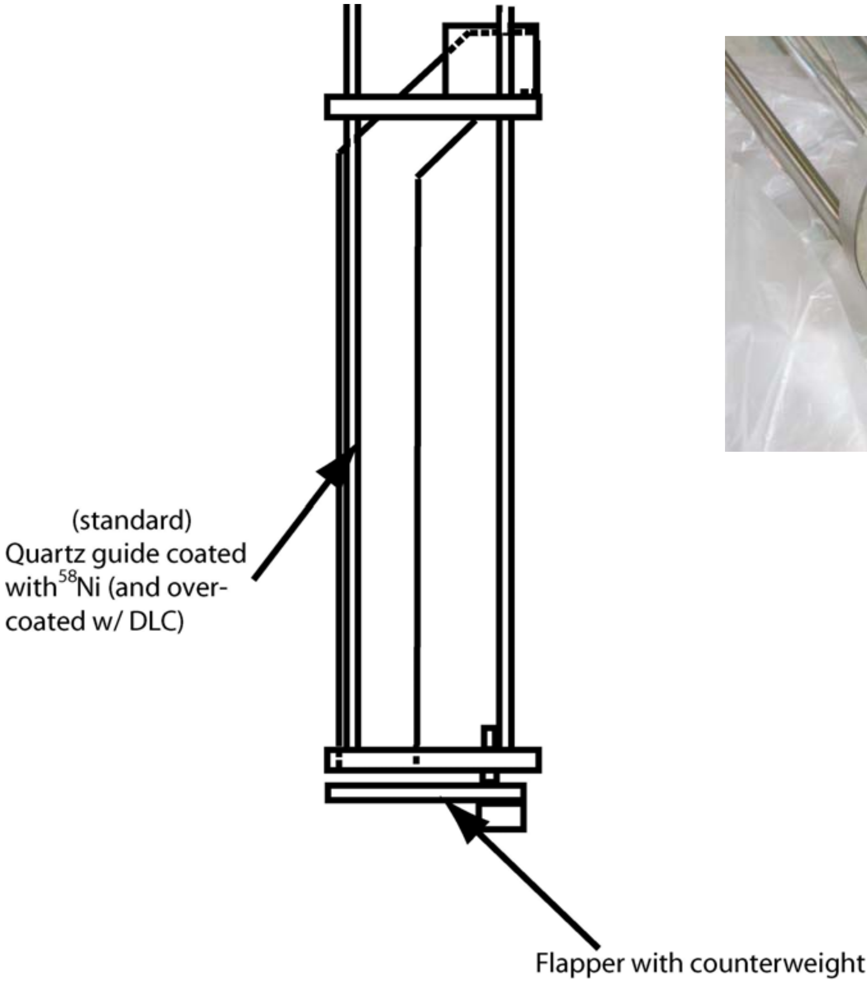
Solution: repair compromises, improve design of flapper

note: all repair solutions exceed the target decay rate of 116 Hz in our proposal

New Source Insert (S. Hoedl and A.Garcia)

• reduces losses from the UCN holding volume, provides a more rapid shutter and uses reliable guide fabrication – sims indicate should be more than adequate!

• Cold tests being carried out this week at LANL…to be followed by beam tests ASAP



The PULSTAR UCN Source Project

- Physics Department:

  C. R. Gould, R. Golub, P. R. Huffman, A. R. Young,
  Y.-P. Xu

- Nuclear Engineering Department:

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

Local research groups with overlapping interests:

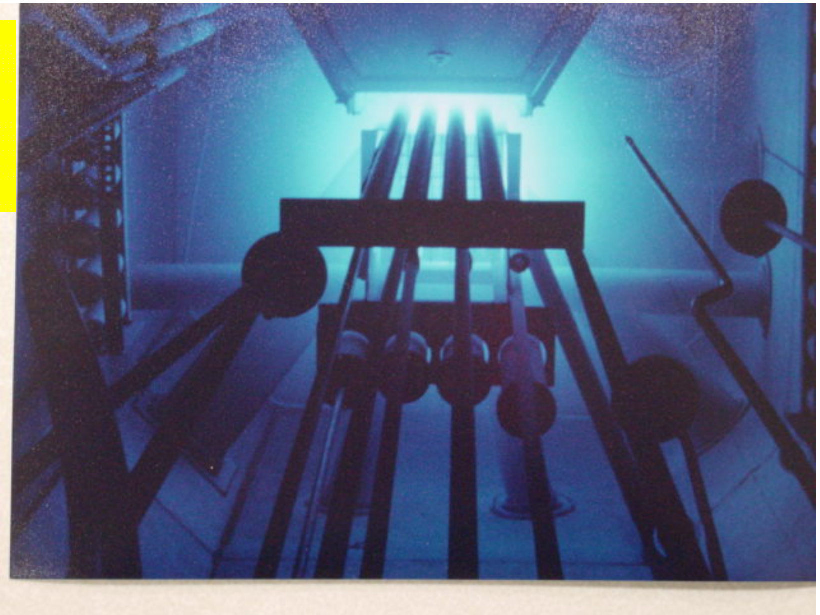
- H. Gao & D. Dutta (in the EDM collaboration)
- H. Karwowski and T. Clegg (weak interactions res.)

Nuclear Engineering Collaborators

• B. Wehring: constructed a CN source at the Nuclear Engineering Teaching Laboratory TRIGA Mark II reactor at University of Texas, Austin

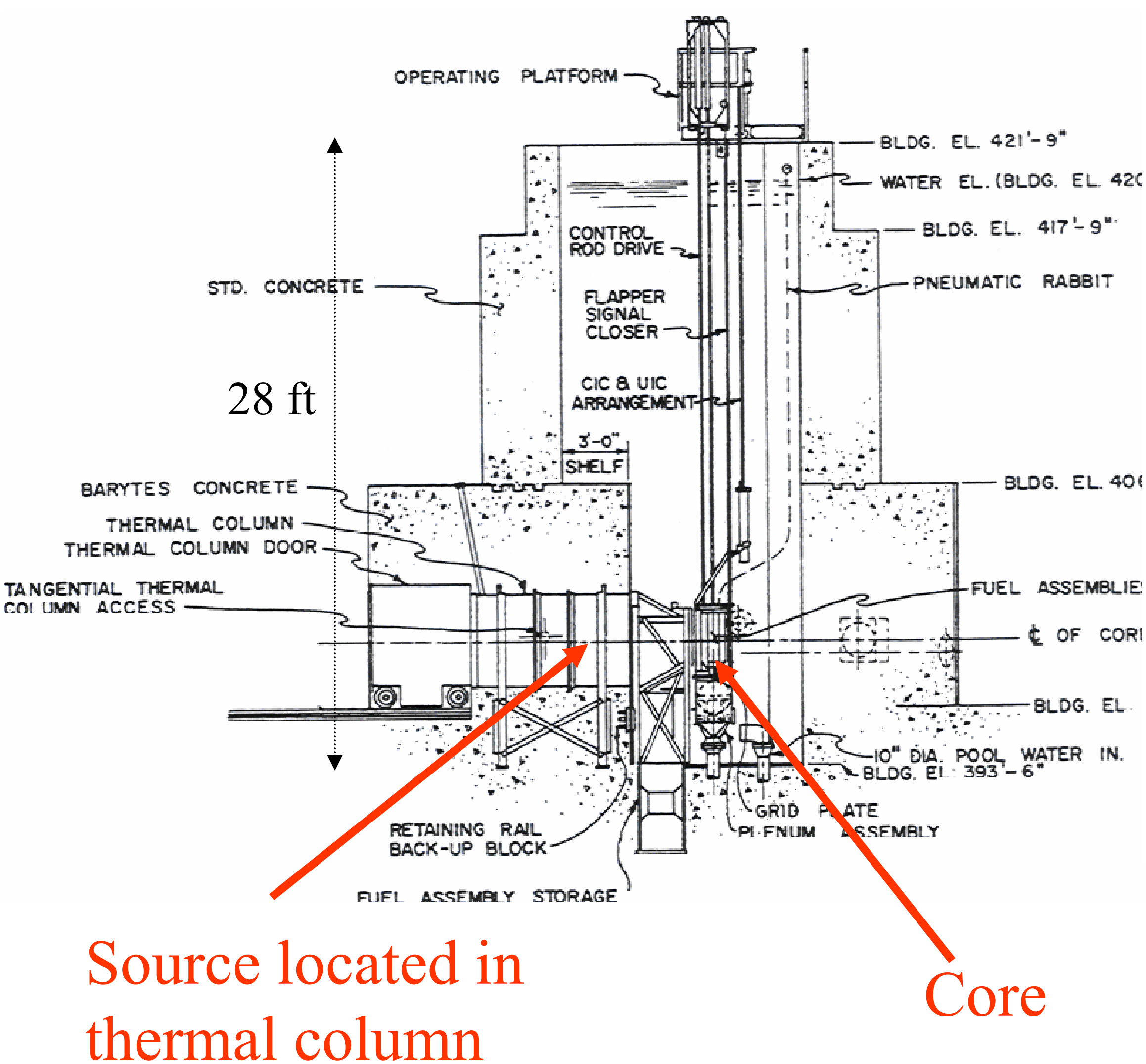
• A. Hawari: active research program in neutron moderator modeling

Side Benefit: Our group is now developing a large number of scattering kernels for various cold moderator and cryostat structural materials



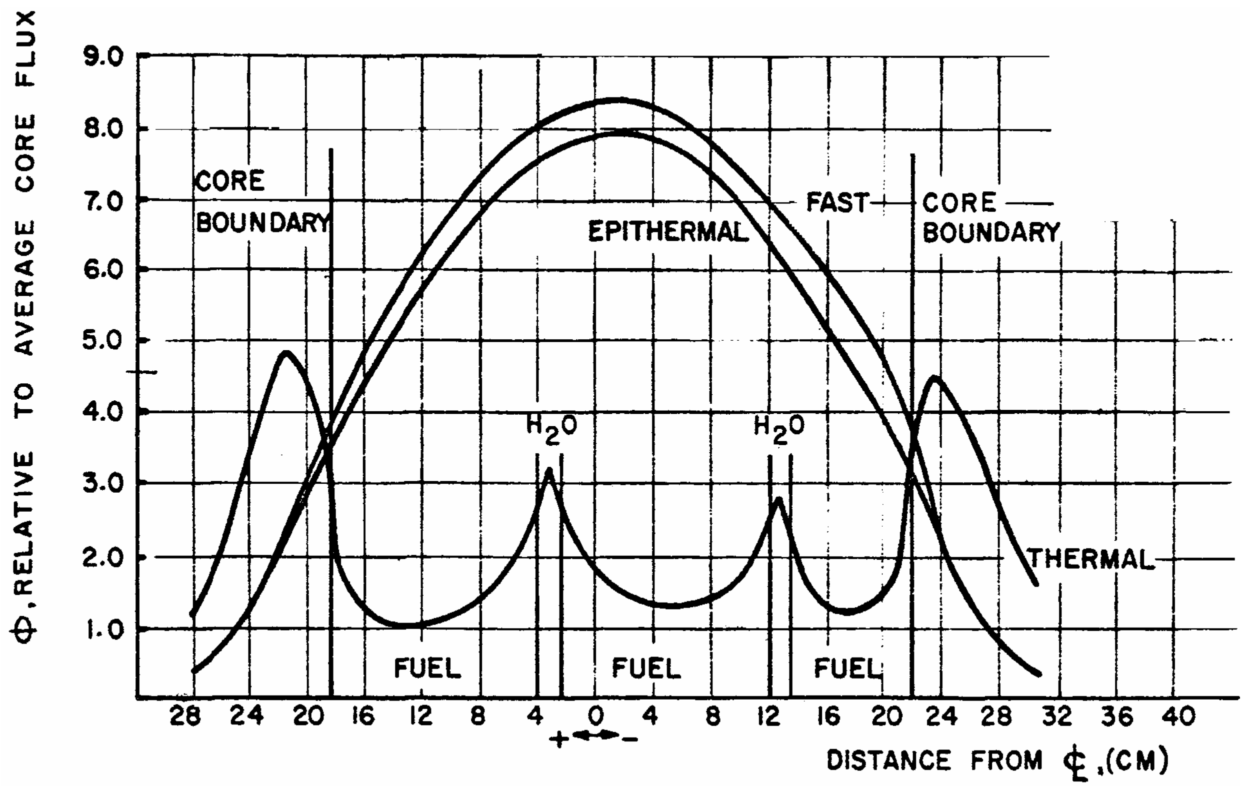
PULSTAR facility is ideal for exploring new ideas for UCN production and experimentation

NCSU PULSTAR Reactor



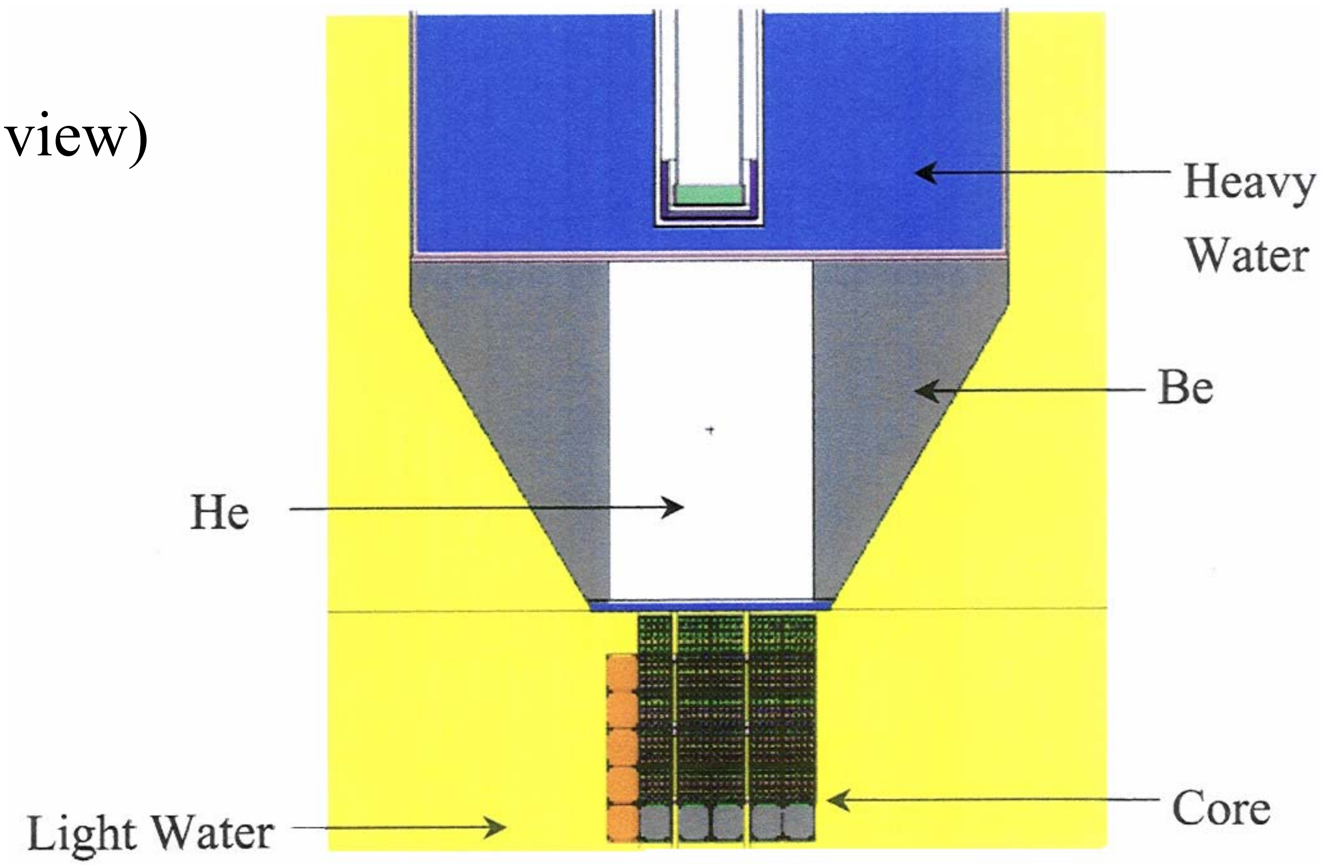
- Sintered UO_2 pellets
- 4% enriched
- 1-MW power
- Light water moderated and cooled
- Just issued a new license for about 10 years of operation.
- PULSTAR design has several advantages for a UCN source:
  - high fast flux leakage
  - long core lifetime

PULSTAR Flux



Conceptual Design I

(top view)

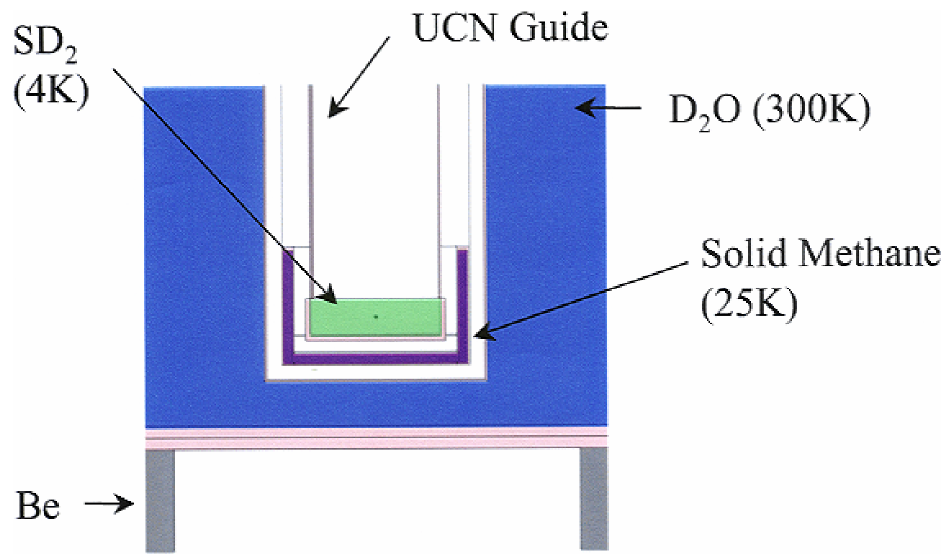


Takes advantage of:

- large fast flux leakage – channel fast and thermal neutrons into D_2O tank
- very low heating – use solid methane moderator

Details of UCN Source

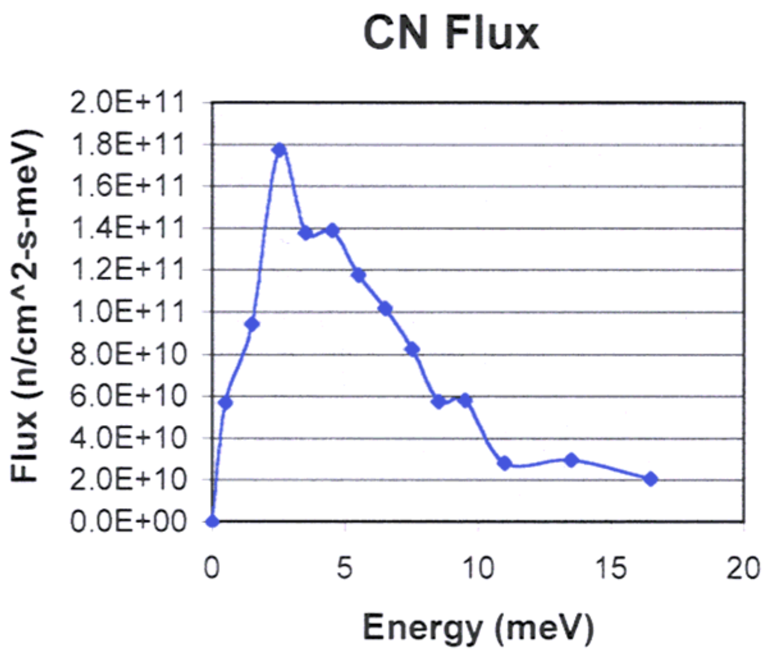
- UCN Converter
  - Solid ortho D_2
  - 4-cm thick
  - 18-cm diameter
- CN Source
  - Solid methane
  - 1-cm thick cup around SD_2



Parametric design calculations

- *CN fluxes* in the UCN converter and *heating rates* by MCNP simulations
- *UCN production rates* by integrating the converter CN energy spectrum with the UCN production cross sections—physics based on LANSCE measurements.
- *UCN intensity* at end of an open UCN guide using UCN-transport calculations.

CN Flux (MCNP)



- Averaged over UCN converter

- Integrated, 0 to 10 meV CN energies

$\varphi = 0.9 \times 10^{12}$ CN/cm^2-s

Neutron and Gamma Heating Rates (MCNP)

- UCN converter, 200 g 1.7 W
- UCN converter chamber, 696 g 3.1 W
- CN source, 558 g 5.6 W
- CN source chamber, 1529 g 6.0 W

Low!

UCN Production Rate and Limiting Density

$I_o = 2.7 \times 10^7$ UCN/s

For $\tau_{SD2} = 43$ ms, $\rho = 1{,}160$ UCN/cm^3

Lifetime assumes SD_2 at 5K, 1.5% para-deuterium, no H_2

Project Benchmarks

- 1.2M dollars over 3 years from the NSF to complete construction, with some DOE funding to the NRP as well
- License already ammended to permit construction of cryogenic apparatus within biological shielding
- Flux in thermal column measured and compared with our MCNP model – excellent agreement (w/in 25%) observed.
- Nose port designed and material ordered to begin fabrication!

SD_2 Source Summary

- For 1MW reactor operating power (optimized):

$$I_o = 3.0 \times 10^7 \text{ UCN/s}$$

$$\rho = 1{,}300 \text{ UCN/cm}^3$$

- Very small heat loads (1.7 W total to UCN converter)

  -cryostat designs straightforward (D. G. Haase)

  -lower operating temperatures feasible

- Accessibility of source is excellent, available year-round, reactor operable by students

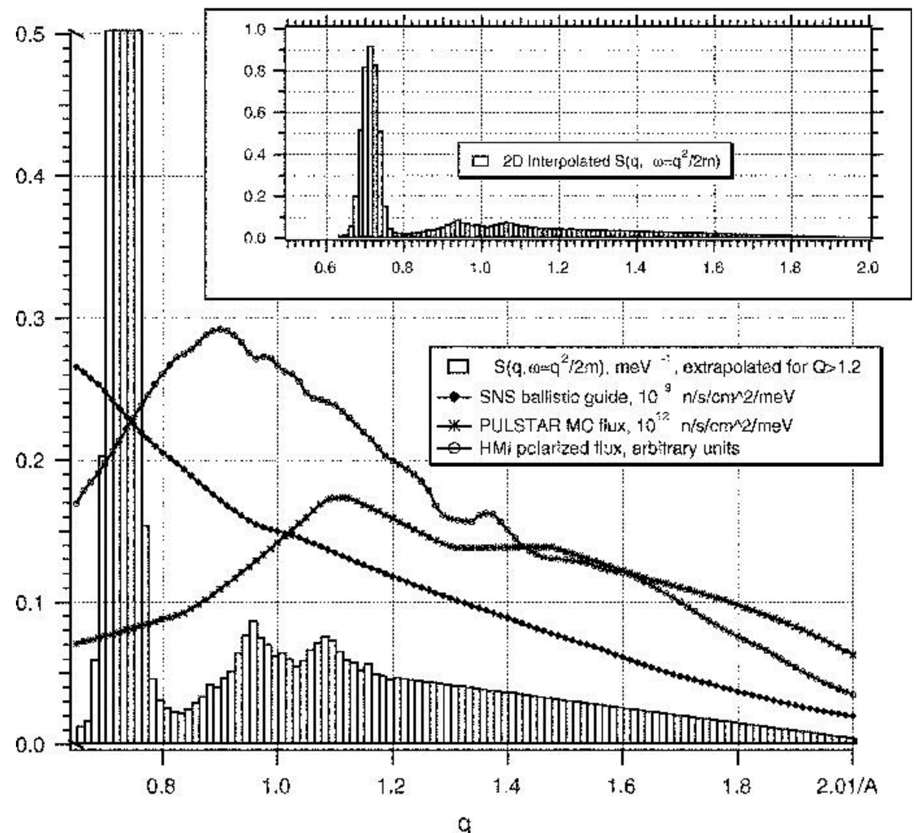
- Upgrade of reactor power to 2MW being planned

Liquid He: R. Golub and E. Korobkina

NCState CN flux well-suited to UCN production in liquid He

Korobkina *et al.* calculate contribution from single and multiphonon prod for various CN distributions

E.Korobkina et al. / Physics Letters A 301 (2002) 462–469



Large gains possible (need to do pilot experiments)

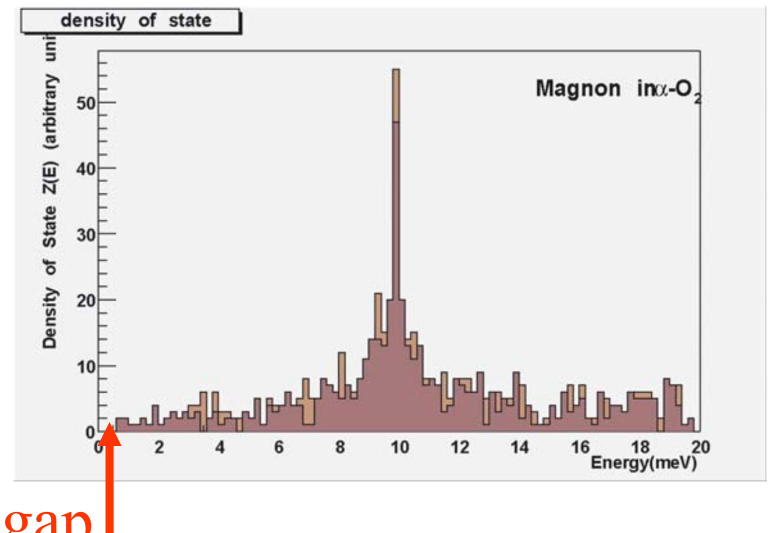
Table 1
Predicted production rates

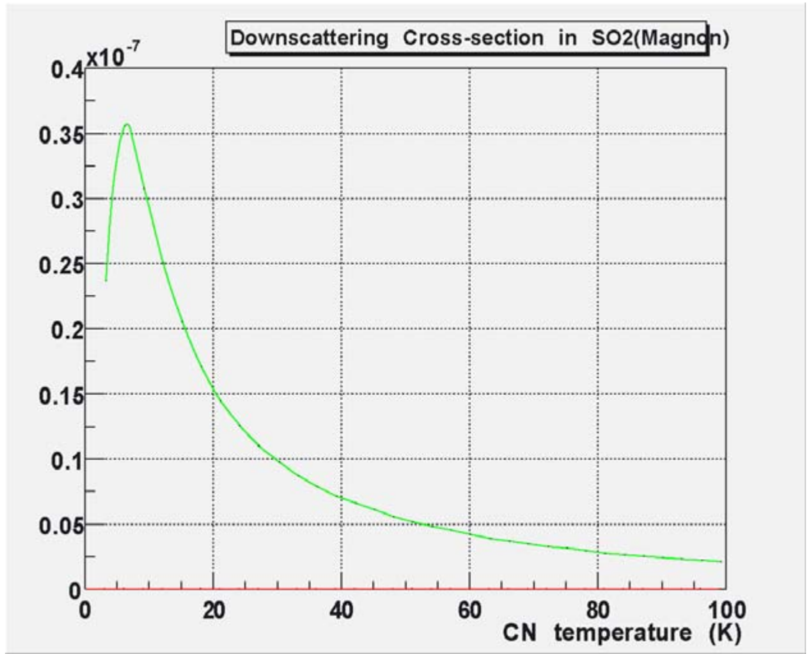
	NC State [a]	SNS ord [a]	SNS ball [a]	HMI a.u.	Maxwell
Multi-ph	490	1.0	0.94	4.7	1.7
Single-ph	375	1.8	2.4	5.5	1.5
Mph/1ph	1.4	0.55	0.4	0.85	1.13

[a] UCN cm^{3} s^{1}.

Another Approach: Solid Oxygen (produce UCN from magnetic scattering)

Solid oxygen – almost perfect antiferromagnet below ~ 20 K neutrons scatter primarily from oxygen spin (magnons, not phonons) C. Y. Liu and A. R. Young, submitted to PRB





Freeze out magnons at 2K

UCN lifetime ~9 x τ_{SD2}

Optimal production w/CN at 8-10K ~ 1.8 R_{SD2}

Limiting UCN density $\rho_{SO2} \sim 16\rho_{SD2}$

If UCN elastic scattering length is long in SO_2, more gains possible!

A Look Ahead

- LHe sources already available at NIST, soon to be available at SNS (with significant technical support) coupled to .89 nm neutron beams -- well adapted to storage experiments

- SD_2 source constructed and being tested at LANL for UCNA "flow-through" geometry and a variety of other experiments

- PULSTAR source will initially be an SD_2 source dedicated to supporting national UCN projects and some applied physics, but we plan to develop other source options (LHe and SO_2) where higher limiting densites and/or production rates are possible.

- Cold moderator development is also planned by M. Snow and C.-Y. Liu at the LENS facility (CN from 12 MeV protons on light targets, moderated by methane), may provide new avenues to optimize UCN yield…

→ We'll hopefully have UCN to work with, to help move the field forward!