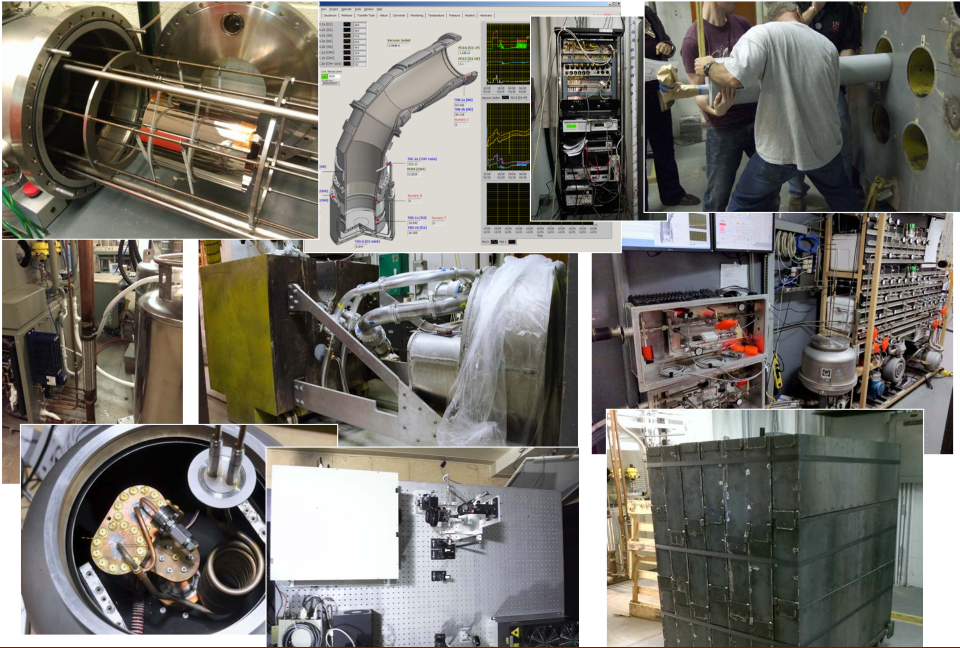
Characterization of the PULSTAR Ultracold Neutron Source

Graham Medlin

Department of Physics
North Carolina State University
glmedlin@ncsu.edu

Tuesday 28th March, 2017



Outline

Neutrons

Temperature	Energy (eV)		Velocity ($^{m}/_{s}$)	Wavelength
10^{11} K	20 MeV		62 000 $^{km}/_{s}$	6 fm
				Nucleus
	10^{6}	Fast	0.05c	
10^{9} K	0.1 MeV		4400 $^{km}/_{s}$	0.1 pm
			10^{6}	
	10^{3}	Slowing down		
			Voyager 1	
11 600 K	1 eV		14 $^{km}/_{s}$	30 pm
		Epi-Thermal	Low orbit	H atom
293 K	25.3 meV	Thermal	2200 $^{m}/_{s}$	0.18 nm
			10^{3}	U atom
	10^{-3}	Cold	Sound	
1 K	60 μeV		110 $^{m}/_{s}$	4 nm
		VCN		CPU node
	10^{-6}		Usain Bolt	
0.003 K	250 neV		7 $^{m}/_{s}$	60 nm
1st gravitational state 1.4 peV ↓	10^{-8}	UCN	Walking 1	Violet light

$$E = \frac{1}{2}mv^2 = \frac{\hbar^2 k^2}{2m} = \frac{h^2}{2m\lambda^2}$$

- Fast neutrons produced in fission and spallation sources
- Moderate to thermal / cold
- Maxwell-Boltzmann temp.

  $$E \sim k_{\mathrm{B}} T$$

- "Convert" to UCN

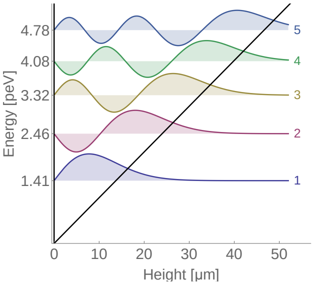
Ultracold neutrons (UCN)

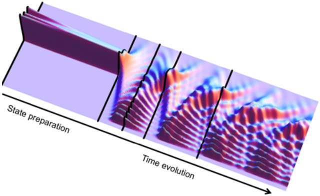
- Total internal reflection, e.g. ^{58}Ni = 340 neV

$$E_{\text{ucn}} \leq V_{\text{m}} = n \frac{2\pi\hbar^2}{m_n} \sqrt{\frac{\sigma_{\text{tot}}}{4\pi}}$$

- Magnetic moment
  $V_B = \vec{\mu}_n \cdot [\vec{B} = 1\,\text{T}] \sim 60\,\text{neV}$
- Earth's gravity, ballistic trajectories
  $V_g = m_n g [h = 1\,\text{m}] \sim 100\,\text{neV}$
- Can prepare mixtures of discrete gravitational states
- Store neutrons for ∼100 s-880 s
- **Most UCN experiments statistics limited**

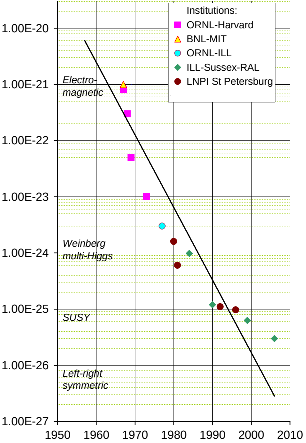
T. Jenke, H. Abele (2014)
10.1016/j.phpro.2013.12.016





Neutron electric dipole moment (nEDM)

C. Baker, et al. (2014)
10.1016/j.nima.2013.10.005



- Frequency shift $\delta\nu_0$ from (anti)parallel fields

$$h\nu_0 = -2\mu_n \left|\vec{B}_0\right| \mp 2d_n \left|\vec{E}_0\right| \rightarrow d_n = h\delta\nu_0/4E_0$$

$$\sigma_d \approx \frac{\hbar}{2\alpha E T \sqrt{N}}$$

- ILL-Sussex-RAL: 545 runs of 1-2 days
  2.5×10^9 neutrons
  $d_n = (-0.21 \pm 1.82) \times 10^{-26}$ e · cm
  $\sigma_{\text{stat}} = \pm 1.53 \times 10^{-26}$ e · cm
  J. M. Pendlebury, et al (2015) PhysRevD.92.092003

Correlation A with UCN (UCNA)

J. D. Jackson, et al. (1957) 10.1103/PhysRev.106.517

$$\omega(\langle J\rangle|E_e,\Omega_e,\Omega_\nu)dE_e d\Omega_e d\Omega_\nu = \frac{1}{(2\pi)^5} p_e E_e (E^0-E_e)^2 dE_e d\Omega_e d\Omega_\nu \xi \left\{1 + a\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_eE_\nu} + b\frac{m}{E_e} + c\left[\frac{1}{3}\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_eE_\nu} - \frac{(\mathbf{p}_e\cdot\mathbf{j})(\mathbf{p}_\nu\cdot\mathbf{j})}{E_eE_\nu}\right]\left[\frac{J(J+1)-3\langle(\mathbf{J}\cdot\mathbf{j})^2\rangle}{J(2J-1)}\right] + \frac{\langle\mathbf{J}\rangle}{J}\cdot\left[A\frac{\mathbf{p}_e}{E_e} + B\frac{\mathbf{p}_\nu}{E_\nu} + D\frac{\mathbf{p}_e\times\mathbf{p}_\nu}{E_eE_\nu}\right]\right\}$$

- β-decay is asymmetric, P violating
- Weak interaction coupling constants
- Polarized free neutrons

$$W(E) \propto 1 + \frac{v}{c}\langle P\rangle A(E)\cos\theta$$

$$A_0 = \frac{-2(\lambda^2 - |\lambda|)}{1+3\lambda^2} \text{ and } \lambda \equiv \frac{g_A}{g_V}$$

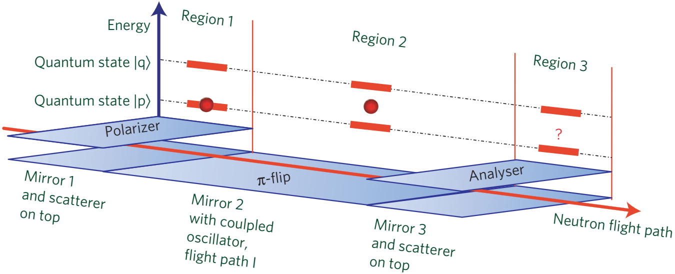
- LANL UCNA
  $A_0 = -0.11945(55)_{\text{stat}}(98)_{\text{syst}}$

Systematic	Corr. (%)	Unc. (%)
Polarization	+0.67	± 0.56
$\Delta_{\text{backscattering}}$	+1.36	± 0.34
Δ_{angle}	−1.21	± 0.30
Energy reconstruction		± 0.31
Gain fluctuation		± 0.18
Field non-uniformity	+0.06	± 0.10
ϵ_{MWPC}	+0.12	± 0.08
Muon veto efficiency		± 0.03
UCN-induced background	+0.01	± 0.02
$\sigma_{\text{statistics}}$		± 0.46
Theory contributions		
Recoil order [21–24]	−1.71	± 0.03
Radiative [25,26]	−0.10	± 0.05

M. Mendenhall (2013) 10.1103/PhysRevC.87.032501

Gravity resonance spectroscopy (GRS)

- Oscillating mirror driving transitions between states matches resonance
- Energy sensitivity of 10^{-14} eV
- Place limits on dark energy/matter, new interactions
- Limited by statistical uncertainty, tiny phase-space
- “qBounce” at ILL: 1 count per minute



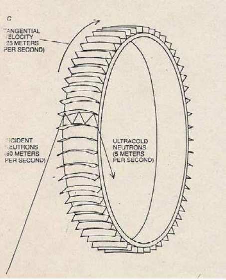
T. Jenke, et al. (2011) 10.1038/NPHYS1970, (2012) arXiv:1208.3875, (2014) 10.1016/j.phpro.2013.12.016

"Traditional" production

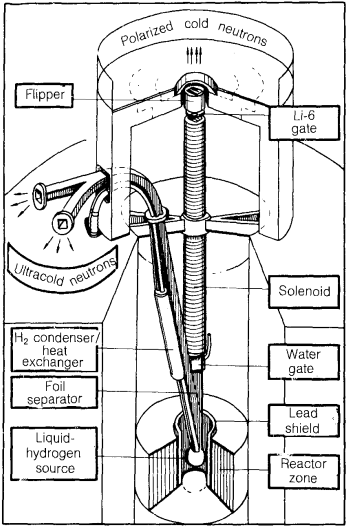
- Present in tail of moderated Maxwell-Boltzmann distribution

$$\Phi(E)\,\mathrm{d}E = \Phi_o \frac{E}{(k_\mathrm{B}T)^2} \mathrm{e}^{\left(-E/k_\mathrm{B}T\right)}\,\mathrm{d}E$$

- Cold moderator, vertical extraction, turbine



- ILL PF2 4×10^6 UCN/s and >36 UCN/cm^3
- Flux limited by Liouville's theorem $\frac{\mathrm{d}}{\mathrm{d}t}\rho(\vec{r},\vec{p};t) = 0$

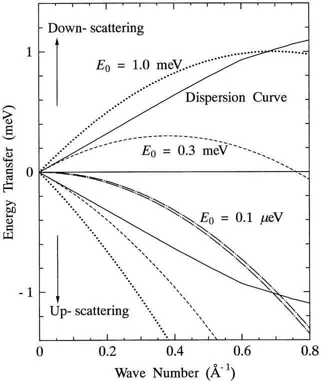


I. Altarev (1986) JETPL

Steyerl, et al. (1986) 10.1016/0375-9601(86)90587-6

"Superthermal" superfluid helium source

Y. Abe, et al. (2001)
10.1016/S0168-9002(00)01009-3



- R. Golub & J. Pendlebury (1977) production by downscatter off Landau roton
- Steady-state UCN density in converter

$$\rho = P \cdot \tau \quad \text{where} \quad \tau^{-1} = \sum \tau_i^{-1}$$

- $\tau_{\beta\text{-decay}} = 880\,\mathrm{s}$
- Upscatter $\tau_+ \sim \exp\left(11\,\mathrm{K}/T_{\mathrm{He}}\right) \rightarrow T_{\mathrm{He}} < 0.7\,\mathrm{K}$
- ^{3}He/^{4}He $< 10^{12}$
- τ_{wall} also

Solid candidates

- Solid phonons can increase production, utilize broader energy range

$$S_{\text{inc}}^{+1\text{ph.}}(\vec{Q},\omega) \propto \frac{1}{M} e^{-2W(\vec{Q})} \frac{Z(\omega)}{\omega} \langle n+1 \rangle \quad \text{and} \quad \frac{Z(\omega)}{\omega} \propto \frac{\omega}{(\Theta_D)^3}$$

Isotope	σ_{tot}	σ_{abs}	Θ_D	Contaminate	σ_{abs}
^4He	1.34	-	20	^3He	5300
H_2	82.03	0.33	120	-	-
D_2	7.64	5.2×10^{-3}	110	H	0.33
$^{15}N_2$	5.21	2.4×10^{-5}	80	^{14}N	1.91
$^{16}O_2$	4.23	1.6×10^{-3}	104	^{17}O(0.038%)	0.236
^{208}Pb	11.34	4.8×10^{-3}	105	^{207}Pb	0.699

C.-Y. Liu (2002) Thesis

- Potential molecules? e.g. CD_4

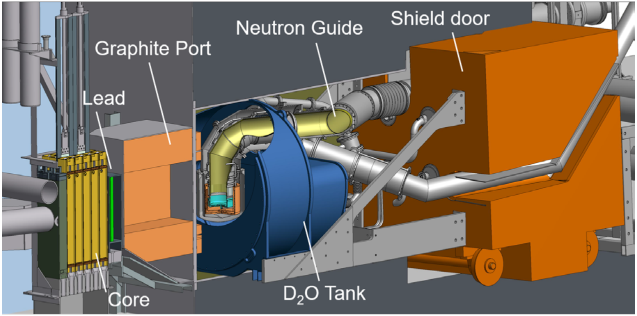
Solid deuterium source

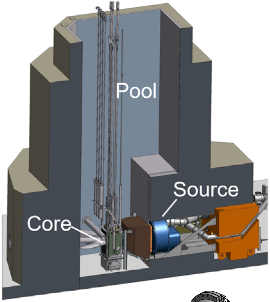
- Order of magnitude faster production than helium
- Nuclear absorption limited

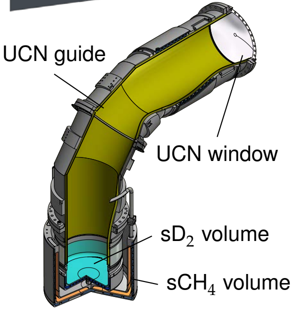
$$\tau_i^{-1} = n_i v \sigma_i(v)$$

- $\tau_{\text{o-D}_2} = 150\,\text{ms}$ → UCN extraction → crystal growth study
- Diminishing returns <5 K → Maintain 5 K under reactor heat
- $\tau_{\text{p-D}_2} = 1.5\,\text{ms}$ → Pre-convert para-D_2 → spin converter
- $\tau_{H_2} = 250\,\mu\text{s}$ → Limit on H_2 → Raman spectroscopy

PULSTAR UCN source





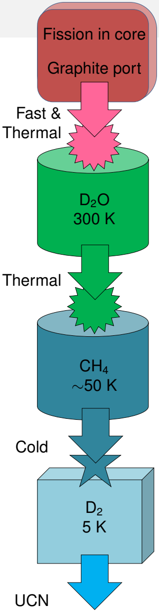


- Thermal column of 1 MW PULSTAR reactor
- Graphite port to transport core neutrons
- 680 L heavy water thermal moderator tank
- 1.4 L $\sim$40 K, cup-shaped, methane cold moderator
- 1 L of 5 K solid deuterium UCN converter

Neutron transport

Goal: Calculate UCN production

- Model fission, transport, and moderation in MCNP
- Benchmark model against activation measurement
- Generate temperature-dependent methane kernel with NJOY
- Model cold spectrum available for UCN production
- Fold with UCN production cross section

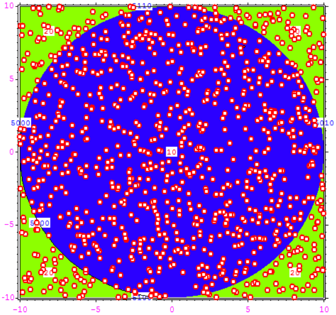


Monte Carlo N-Particle (MCNP)

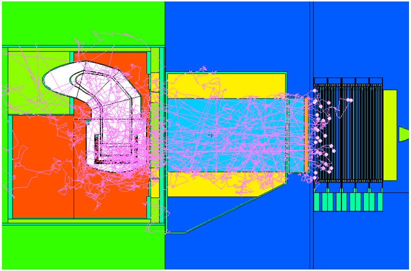
Monte Carlo method

- Random sampling approx. analytical solution
- Fire 10^8 neutrons at a disk inscribed square

$$4(\text{tally}) = 3.141\,46 \pm 0.0004$$
$$\text{vs.} \quad \pi = 3.141\,59\ldots$$



28 neutrons <25 meV to sD_2 per 20 000 generated



MCNP

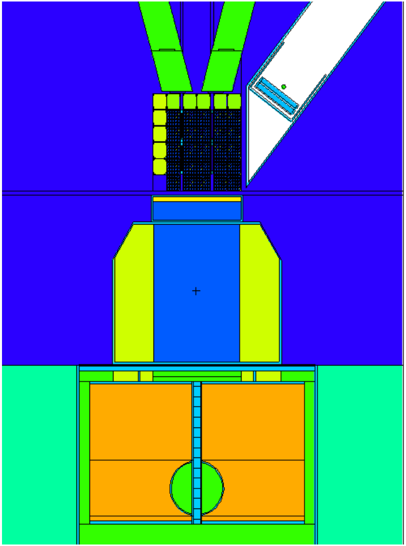
- Generate particle, calculate next surface intersection
- Material sets collision, interaction probability, e.g. free gas or $S(\alpha, \beta)$
- Particles tallied at virtual detector

MCNP model

- Existing PULSTAR model
- Criticality calculation (KCODE)
- Benchmarked against thermal column

$$\frac{\Phi}{(\text{tally})} = P\frac{\bar{\nu}}{Q} = (1\,\text{MW})\left(\frac{2.46\,\text{n}/\text{fission}}{200\,\text{MeV}/\text{fission}}\right)$$

- Add transport system, test tank geometry
- Standard ENDF material libraries



Activation measurement

- Gold foil neutron activation

$$ {}^{197}_{79}\mathrm{Au} + \mathrm{n} \rightarrow {}^{198}_{79}\mathrm{Au} \rightarrow {}^{198}_{80}\mathrm{Hg} + \mathrm{e}^{-} + \gamma $$

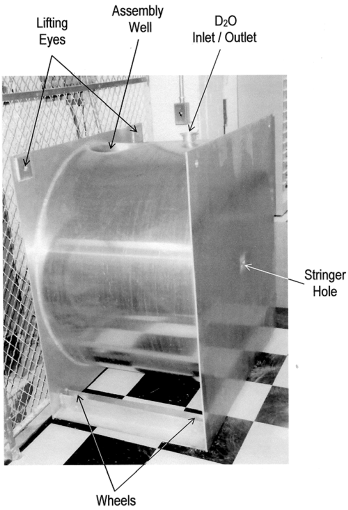
$$ R = N_o \int \mathrm{d}E\, \sigma_a(E) \Phi(E) $$

- Cadmium strongly absorbs $<$0.5eV
- Gold cross-section 1/v below cutoff
- Assume moderated flux

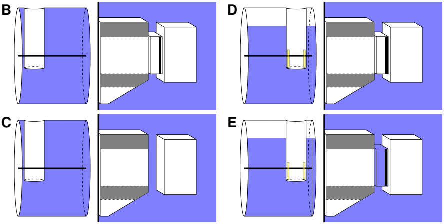
$$ \sigma_a(E) = \sigma_a^o \sqrt{kT_o/E} $$

$$ \Phi(E) \propto E \exp\left(-E/kT_o\right) $$

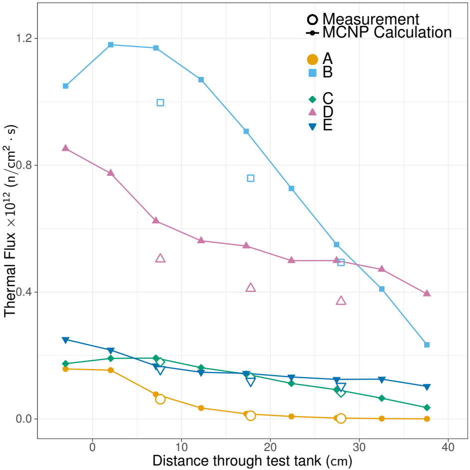
- Test tank simulates source tank
- Foils alternately cadmium-shielded



Thermal neutron results

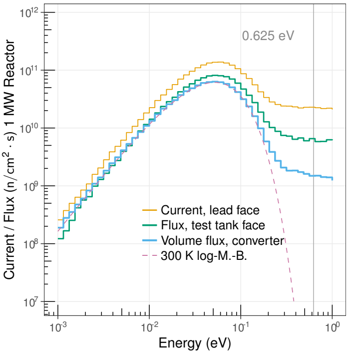


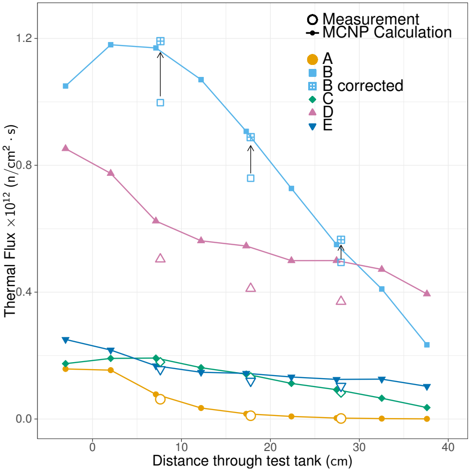
- 80% reduction without shielding box
- 15% disagreement with shielding box
- Shape agrees
- 30% reduction due to void



Epithermal correction

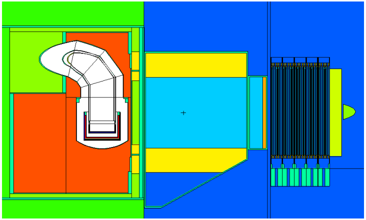
- Significant epithermal flux
- Maxwellian assumption under-represents epithermals
- Using MCNP spectrum, ∼1%
- MCNP acceptably benchmarked





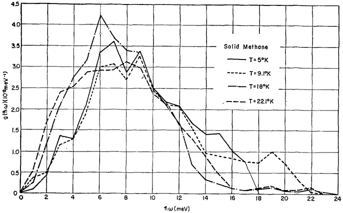
Source model & phase I methane

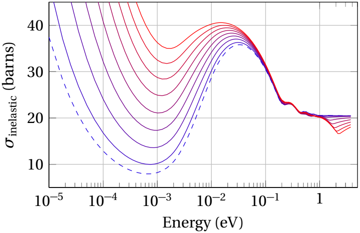
- Source modeled in MCNP
- Treated D_2 as vacuum
- Tallied avg. flux over converter



- Methane $S(\alpha, \beta)$ at 22 K library from LEAPR
- Harker & Brugger 1967 measurements
- No expected behavioral change $>$65-22 K
- Created libraries 22-60 K

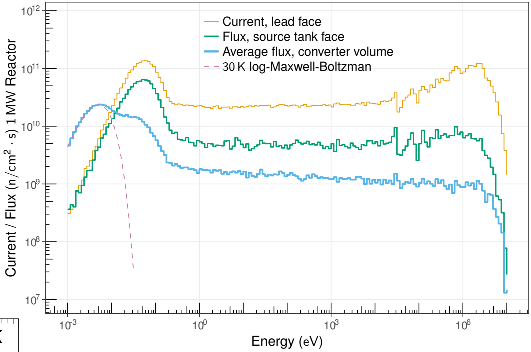
Y. Harker, R. Brugger (1967)
10.1063/1.1841024

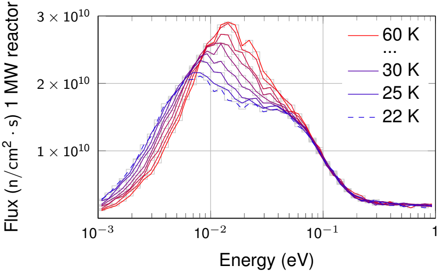




Cold flux

- 50% from core epithermals
- Cold flux not fully thermalized
- Increasing moderator thickness reduces total flux
- Production not very temperature dependent

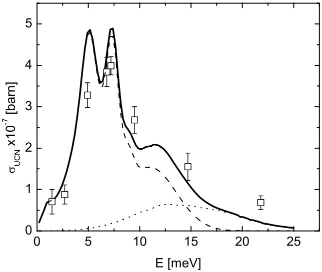


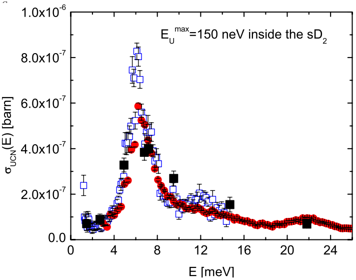


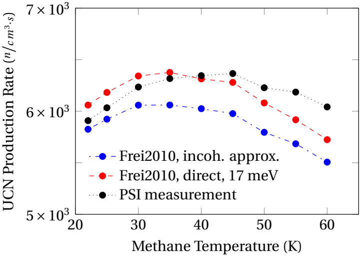
- Run moderator warmer, less cryogenic demand
- Avoid stored energy problem

UCN production

A. Frei, et al. (2011)
10.1209/0295-5075/92/62001







- Production rate 6×10^3 $\mathrm{UCN}/\mathrm{cm}^3 \cdot \mathrm{s}$
- Density rough estimate...
  - 2% para
  - 0.13% H_2
  - 40 ms survival time
- 250 $\mathrm{UCN}/\mathrm{cm}^3$

Outline

Molecular deuterium spin states

- Quantum rotor, $J = 1$ state at 7.4 meV

$$E_J \approx \frac{\hbar^2}{2I} J(J+1) \rightarrow \Delta(\Delta E)$$

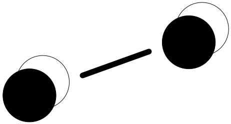
- Independent *para* (J odd) *ortho* (J even) species

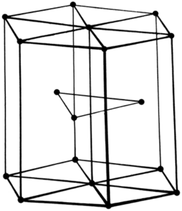
$$\{\psi_{\text{rotational}} \cdot \psi_{\text{spin}}\}_{\text{symmetric}} \rightarrow \Delta J \pm 2$$

- Total spin $S = 0, 1, 2$: 1,3,5-fold degenerate
- At low T, $J = 1$ still present

$$N_J \propto (2J+1) g_S \mathrm{e}^{-E_J / k_\mathrm{B} T}$$

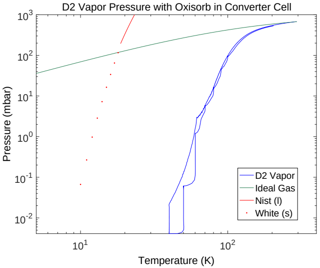
- Can upscatter UCN by spin flip, $J = 1 \rightarrow 0$
- Must convert *para*-deuterium prior
- Low temperature magnetic catalyst





Spin converter

- U-shaped copper cell
- Coaxial heat exchanger
- Installed without breaking seal
- Oxisorb and iron hydroxide catalysts
- Adsorbs >60 liters gas
- Vapor pressure not thermometer
- Expected para-content on gas panel



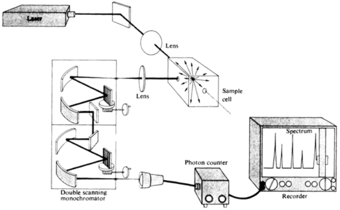
Raman spectroscopy

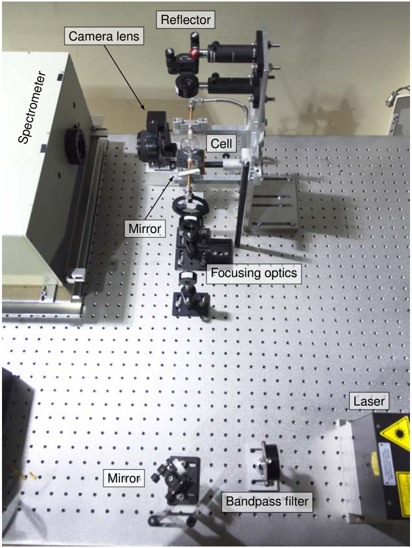
- Sensitive to rotation in diatomics
- Direct measurement
- Reference eliminates system dependencies

$$E_{J+2} - E_J = hc\left(\frac{1}{\Lambda} - \frac{1}{\lambda}\right)$$

$$r = \frac{1}{2}\frac{I'_{\text{para}}/I'_{\text{ortho}}}{I^o_{\text{para}}/I^o_{\text{ortho}}}$$

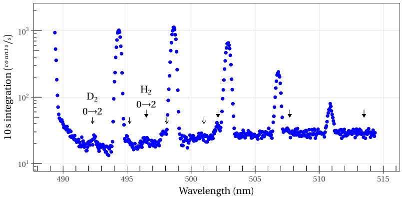
E. Hecht, *Optics*

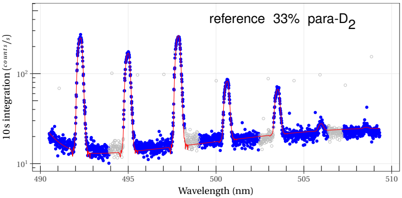


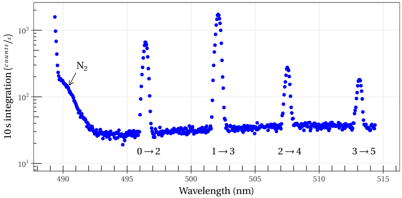


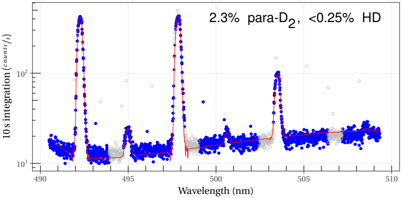
Raman spectra

- More sensitive to H_2, in these samples, stricter limit than HD
- Could put limit on O_2, N_2

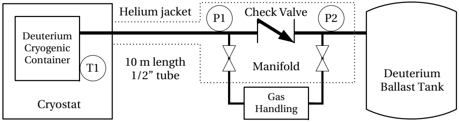








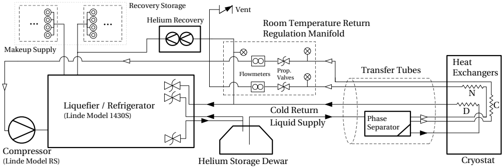
Gas handling



- High-purity, flexible design
- Remains at saturation during liquefaction
- Passive gas return

Helium system

- Hybrid liquefier and refrigerator, modified for continuous operation
- Demonstrated independent control of cooling loops
- Maintains cryostat temperature with electric heaters simulating reactor load



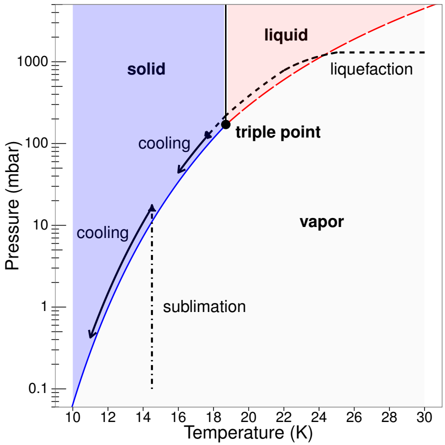
Outline

Crystal growth study

- Elastic scattering shortens mean free path, impedes UCN extraction
- Other groups have observed method of crystal growth impacts production
- How do crystal properties affect UCN production in our source?
- Limited access when installed

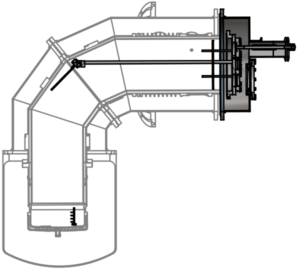
Before neutrons, goals:

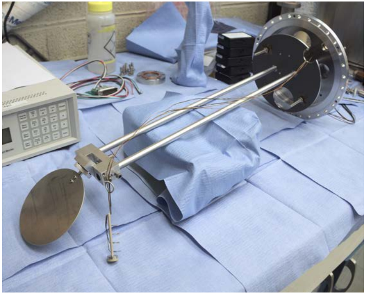
- Translate measured P/T into crystal T
- Temperature-gradient in crystal
- Optical transparency
- Effect of IR load

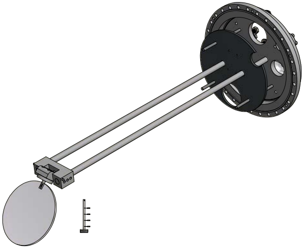


Design

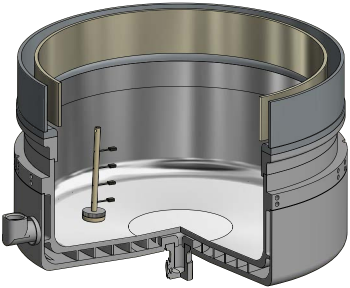
- Re-usable, install without disassembly
- Replace UCN foil window
- Pressure- SS bellows feedthrough
- Optical-“Dentist’s mirror”
- IR- heated plate
- T-gradient- stand lowered from mirror





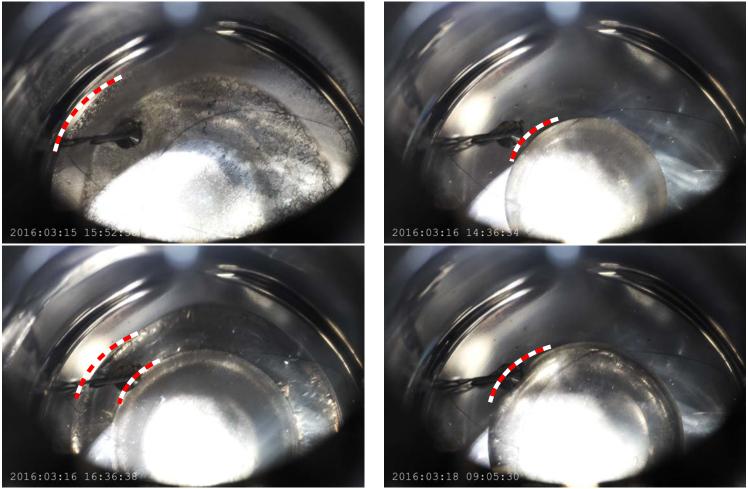


Design



Solid movement

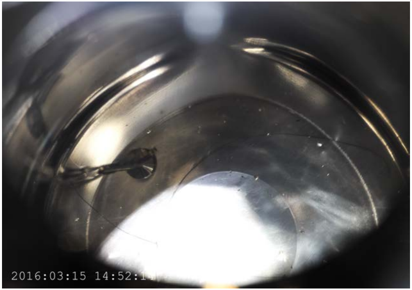
- Above 10 K, high gradient in vapor pressure causes migration to cold spots



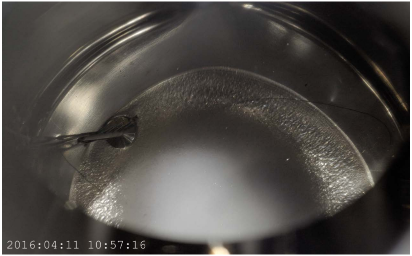
Video

Beginning sublimation

(A1) <5.4 K, 8.2 K, 10 mbar



(C1) 9.5 K, 18.3 K, 40 mbar



(D1) 8.4 K, 16.2 K, 15 mbar

(E1) 9.7 K, 17.8 K, 16 mbar

Full inventories

(B2) Cold sublimation

(B4) “Annealed”

(B5) Melt & re-freeze

(C2) Warm sublimation

Surface defects

(C2) Warm sublimation

(C2) Cooled

(C4) Pulsed heater

(C5) Warming

(C5) Warming

Crystal study conclusions

Optical

- Optically transparent from liquid or high temperature sublimation
- D_2 migration 10-18.7 K can create dome shape
- “Annealing” can alter crystal appearance
- Rapid temperature changes create surface irregularities

Temperature

- Center of container at He inlet is significantly colder
- Pressure accurately reflects surface temperature
- External sensors relationship is circumstance dependent
- Surface temperature increases with sublimated thickness
- Effect of larger IR load still unknown

Conclusion

Recap

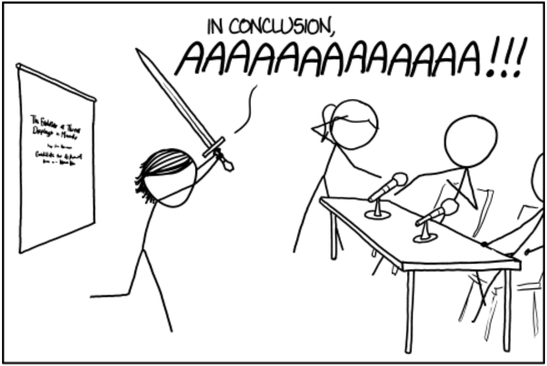
- Current neutronics model
- Built and tested gas handling system, spin converter
- Completed and tested cryostat, helium system, Raman system
- Designed, built, ran crystal study

Current status

- Source
  - Chilled water improvement
  - Shielding and neutron safety review
- Neutronics model publication
- Crystal study publication?

Questions?

1. Introduction
   - UCN
   - Example experiments
   - Production
2. Neutron transport model
   - MCNP model
   - Foil activation benchmarking
   - Methane temperature
   - UCN production
3. Source commissioning
   - Spin converter
   - Raman spectroscopy
   - Gas handling
   - Cryogenics
4. Crystal growth study



THE BEST THESIS DEFENSE IS A GOOD THESIS OFFENSE.

EXTRA SLIDES