

Solid Oxygen as an Intense Ultracold Neutron Source

Chen-Yu Liu

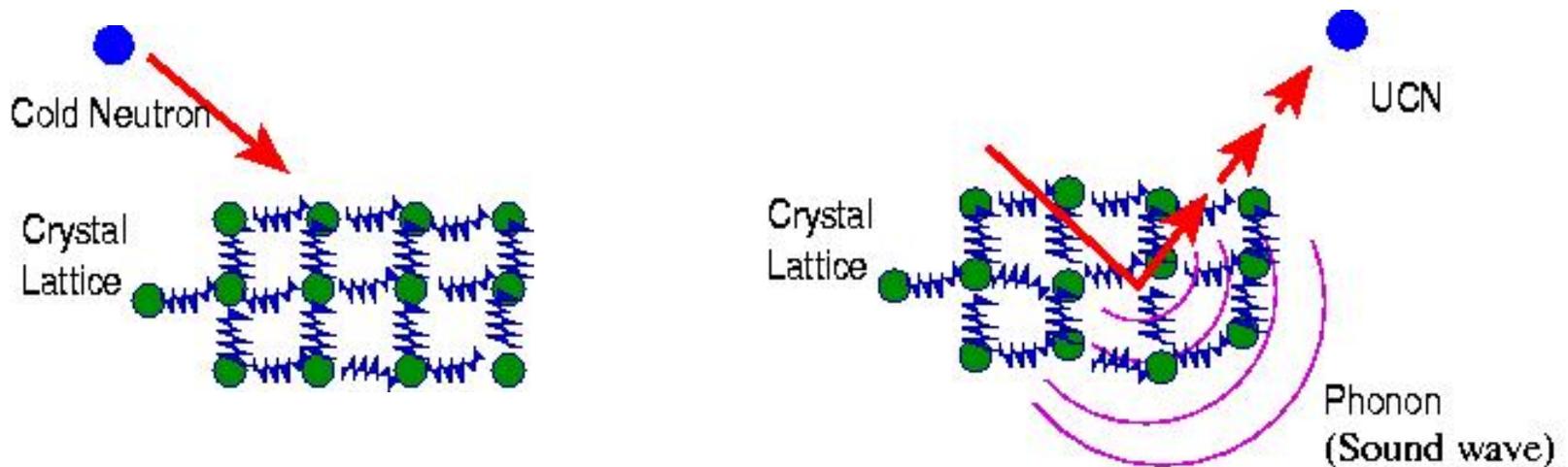
NP08, March 6, 2008
Mito, Ibaraki, Japan

INDIANA UNIVERSITY IUCF

Superthermal UCN Source

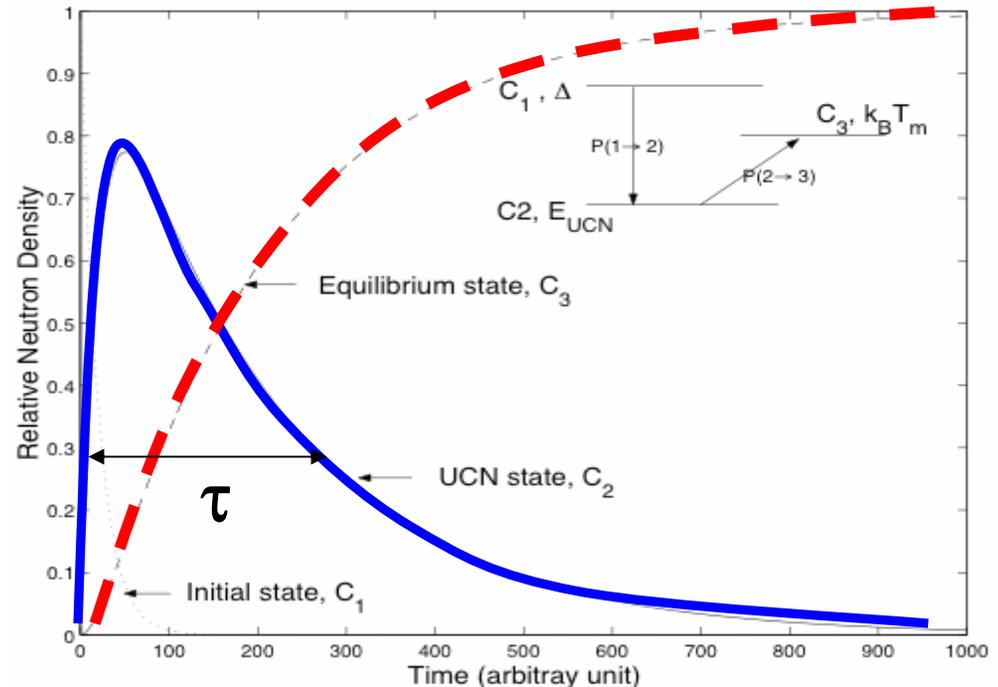
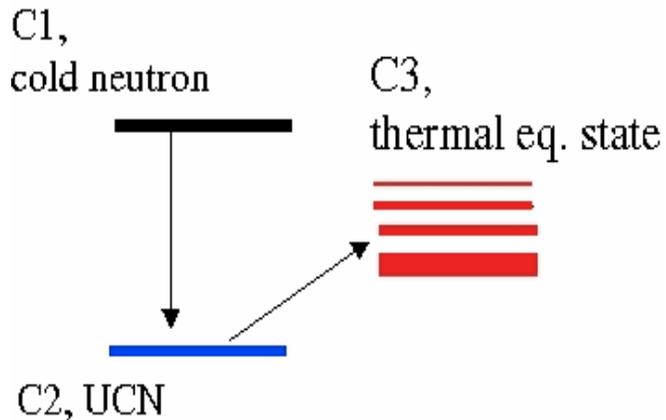
R. Golub and J. M. Pendlebury, *Phys. Lett*, A53, 133 (1975)

- Cold neutrons downscatter in the solid, giving up almost all their energy, becoming UCN.



- UCN upscattering (the reverse process) is suppressed by cooling the moderator to low temperatures.

Dynamics of UCN Production -- Defeat thermal equilibrium

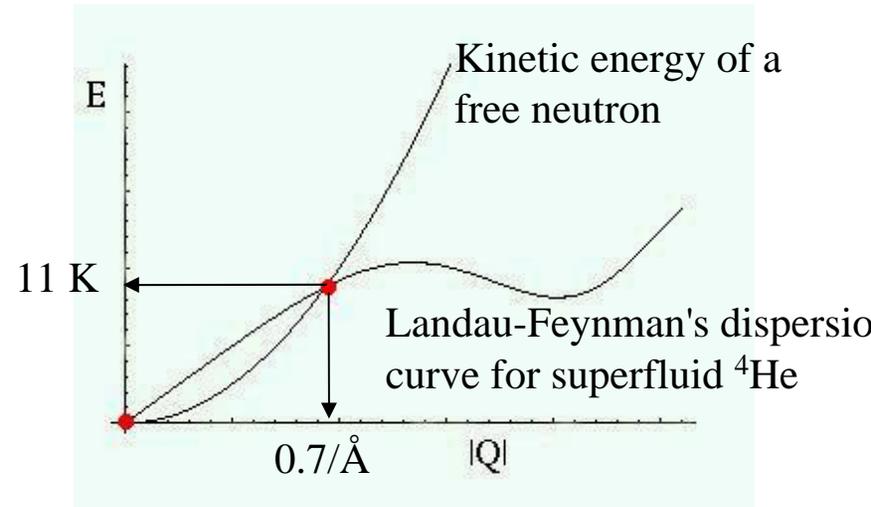
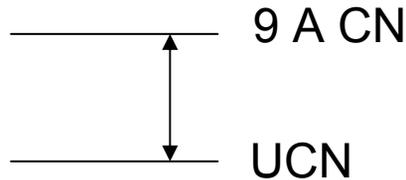


- Lifetime of UCN in the source material: the critical parameter in the establishment of large UCN densities.
 - Extract UCN out of the source before it is thermalized
- ⇒ **Spallation N source** + Separation of the source and the storage
+ a UCN Valve

UCN production in Superfluid ^4He

- Superfluid ^4He
 - Energy excitation is isotropic.
 - Neutron scattering is isotropic.

Two level system:



- UCN can accumulate until the production rate = loss rate

$$\rho_{ucn} = P \times \tau = (\Phi_0 \sigma_{down}) \left(\frac{1}{n \sigma_{up} v} \right) \propto \frac{\sigma_{down}}{\sigma_{up}} = \frac{1 + n(\omega)}{n(\omega)} \sim \exp(\omega / T)$$

$$n(\omega) = \frac{1}{\exp(\omega / T) - 1}$$

Superthermal gain⁴

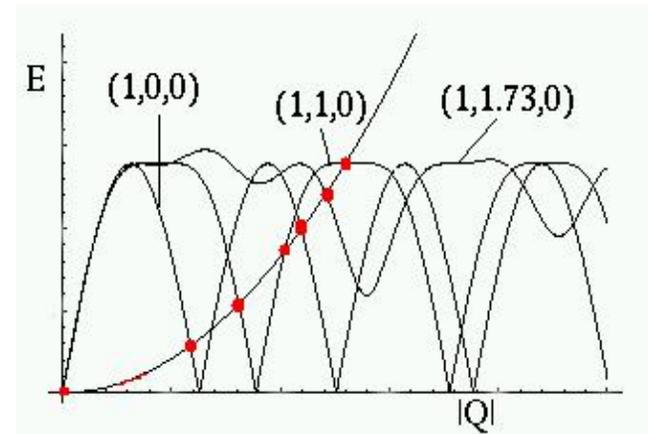
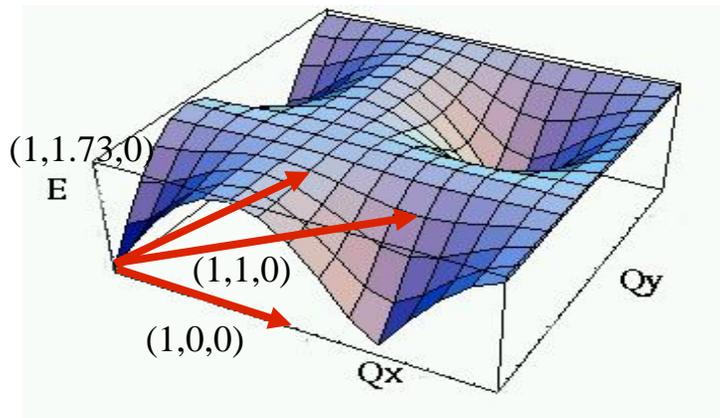
UCN loss in Superfluid ^4He

- UCN production rate: $P = 7.2 \frac{d^2\Phi}{d\lambda d\Omega} \frac{1}{\lambda_{wall}} \text{ UCN/cm}^3\text{sec}$
- UCN density: $\rho_{ucn} = P \times \tau \propto \sigma_{down} \left(\frac{1}{\sigma_{up}} + \frac{1}{\sigma_{\beta}} + \frac{1}{\sigma_{nucl.ab.}} + \dots \right)$
(Limited by loss)
- The figure of merit: σ_s / σ_a

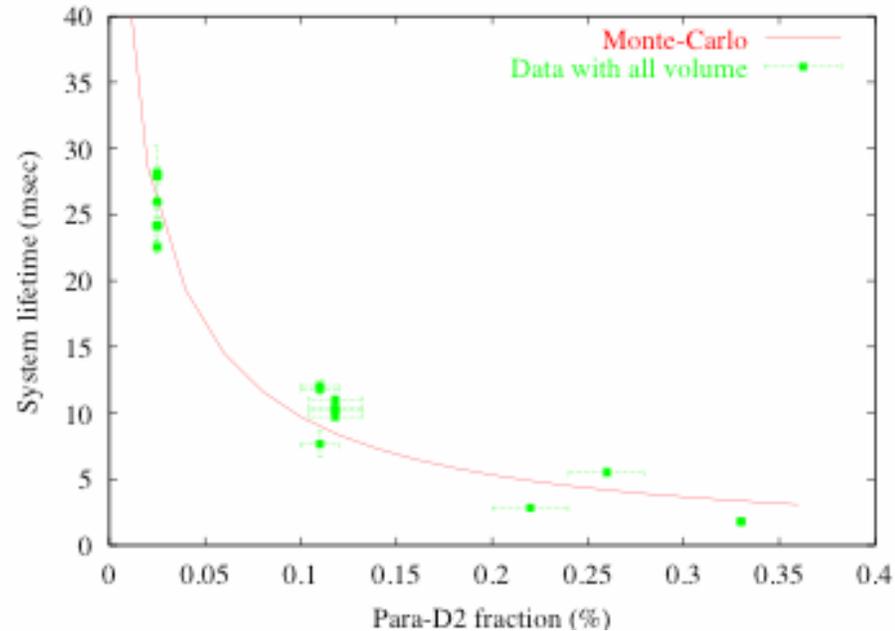
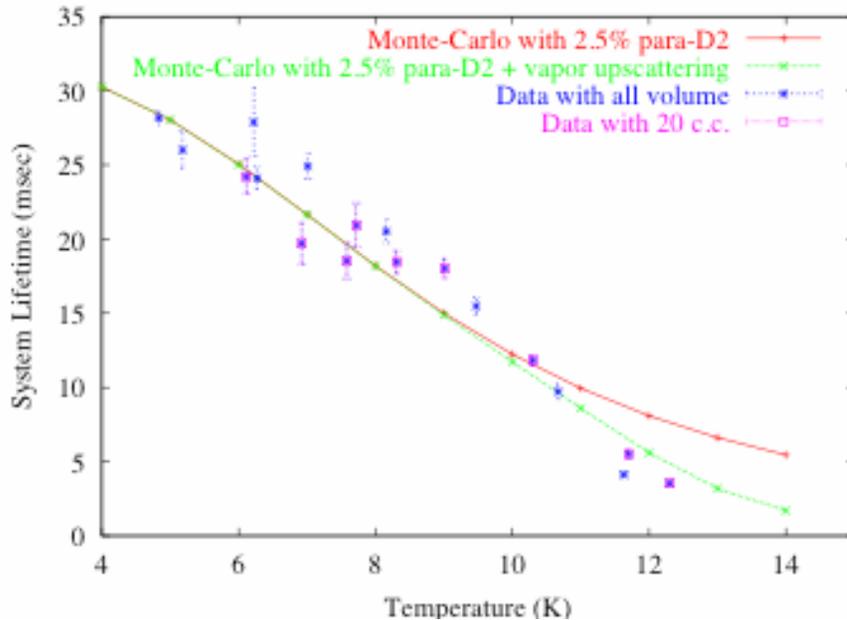
Isotop	σ_{coh}	σ_{inc}	σ_a	σ_s/σ_a	purity	Debye T
^2D	5.59	2.04	0.000519	1.47×10^4	99.82	110
^4He	1.13	0	0	∞		20
^{15}N	5.23	0.0005	0.000024	2.1×10^5	99.9999	80
^{16}O	4.23	0	0.00010	2.2×10^4	99.95	104
^{208}Pb	11.7	0	0.00049	2.38×10^4	99.93	105

UCN production in Solid D₂

- Incoherent scattering ($\sigma_{\text{inc}} = 2.04 \text{ barn}$)
 - The difference of singlet and triplet scattering
- Coherent contribution ($\sigma_{\text{coh}} = 5.59 \text{ barn}$)
 - In a cold neutron flux with a continuous spectrum, **more neutrons could participate in the UCN production.**



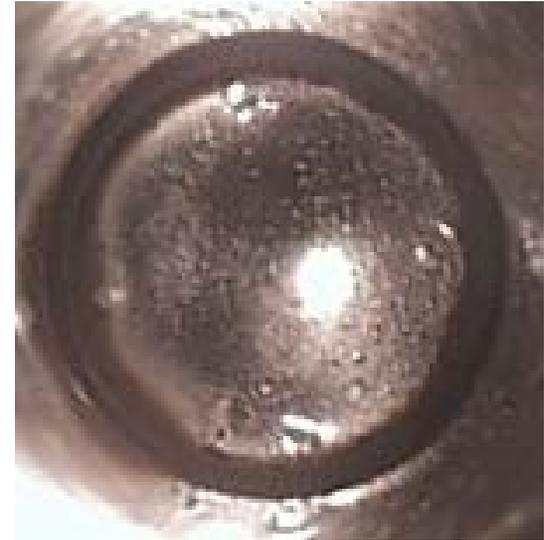
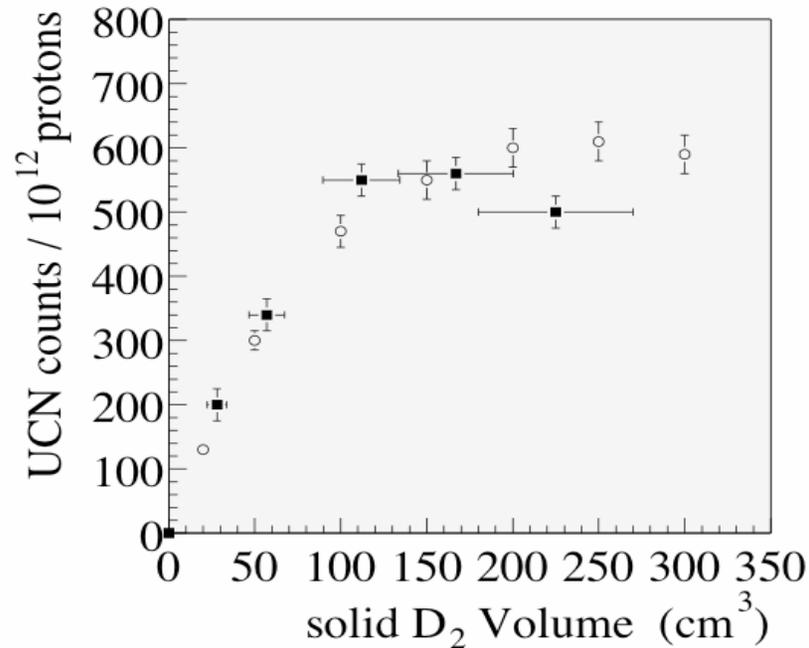
UCN lifetime in S-D₂



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

- Superthermal temperature dependence.
- Para-D2 upscattering time: **1.2 ± 0.2** ms.

Volume Scan

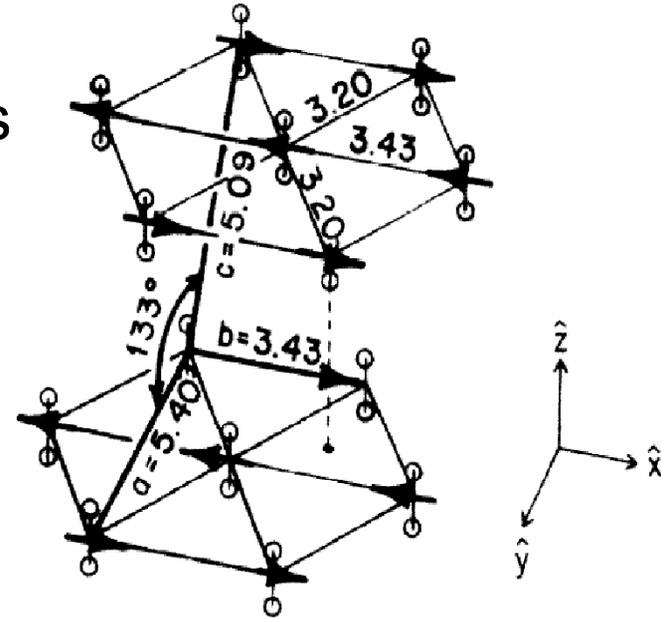


- UCN yield saturates above 200 c.c.
 - mean free path = 8 cm
 - Results from UCN incoherent elastic scattering (random walk).
- Additional scatterings due to the finite crystal effects do not dominate and limit the UCN extraction.

Solid Oxygen as a UCN Source

- Electronic spin $S=1$ in O_2 molecules
- Nuclear spin = 0 in ^{16}O
- Anti-ferromagnetic ordering
 - α -phase, $T < 24K$.

P.W. Stephens and C.F. Majkrzak, Phys. Rev. B **33**, 1 (1986)



UCN Production in $S-O_2$

- Produce UCN through magnon excitations.
 - Magnetic scattering length ~ 5.4 fm.
- Null incoherent scattering length.
- Small nuclear absorption probability.

\Rightarrow A very large source possible.

Neutron Scattering in Solid O₂

- Spin(n) -Spin(e) coupling

$$V(r) = -\mu_N \cdot H = -\gamma\mu_N \sigma \cdot \left\{ \nabla \times \frac{\mu_e \times r}{r^3} \right\}$$

$$V(k) = \gamma_0 \sum_l \sigma \cdot \underbrace{\tilde{k}}_{\text{(Spin)}} \times \underbrace{(\tilde{S}_l \times \tilde{k})}_{\text{(Translation)}} e^{ik \cdot r_l}$$

(Spin) × (Translation)

$$\frac{d^2\sigma}{d\Omega d\omega} \propto (1 - \tilde{k}_z^2) \sum_{l,l'} \langle \hat{S}_l \hat{S}_{l'} \rangle \times \langle e^{ik \cdot r_l - k \cdot r_{l'}(t)} \rangle$$

\Downarrow
 (1+magnon)

\Downarrow
 (1+phonon)

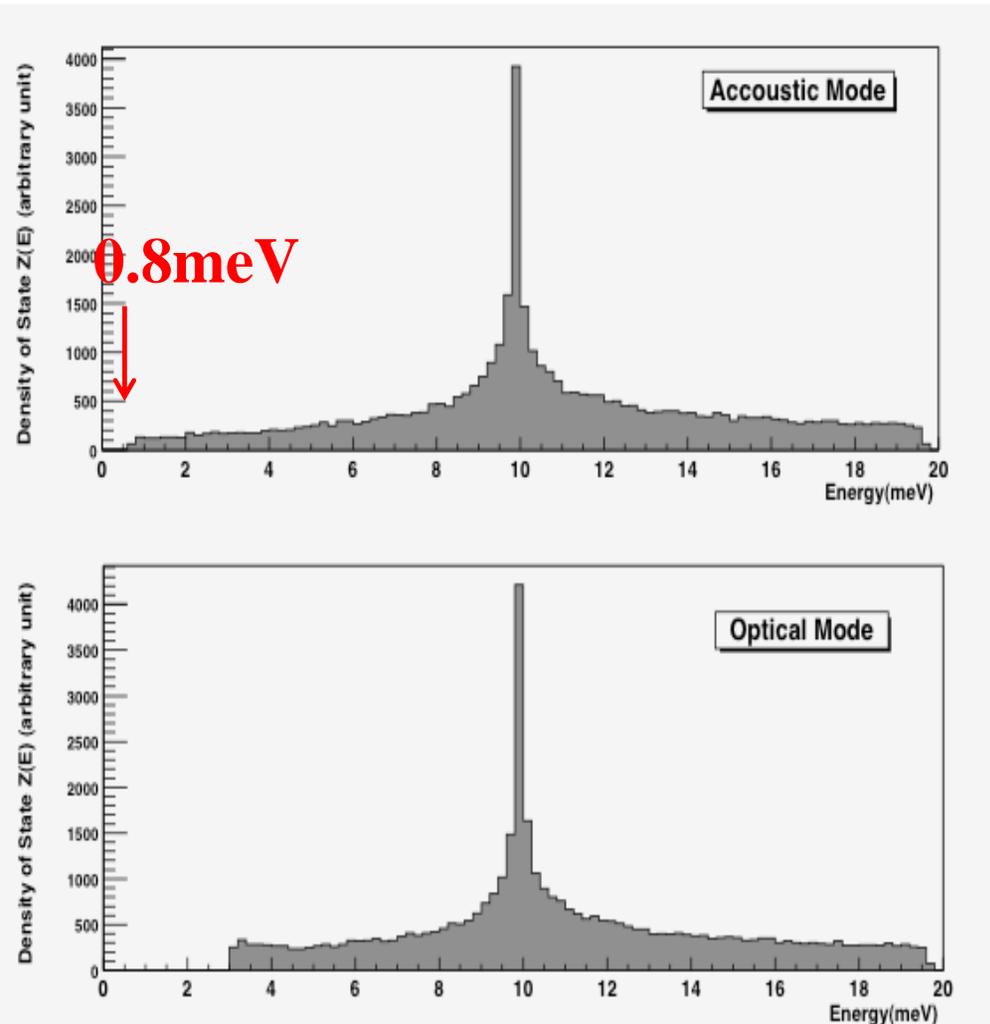
(1+magnon) × (1+phonon)



Elastic Bragg + Magnon Scatt. + Magneto-vibrational Scatt. + both magnon, phonon

Neutron-Magnon Scattering in S-O₂

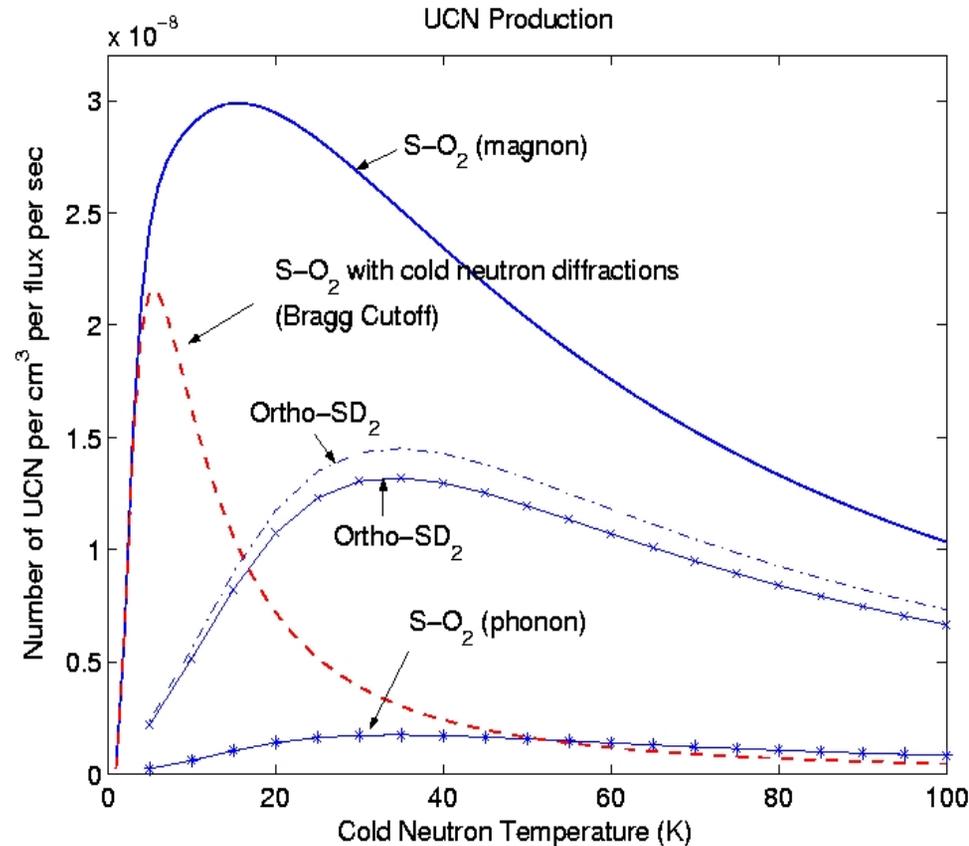
Density of States (Magnon)



- AF magnon: scattering amplitude prefers low momentum transfers.
 - Needs a colder neutron spectrum for the optimum UCN production.
- Magnon production energy gap $\sim 0.8\text{meV}$
 - Magnons partially frozen at $T < 8\text{K}$.
 - Significantly reduce the UCN upscattering rate.

UCN production in Solid Oxygen

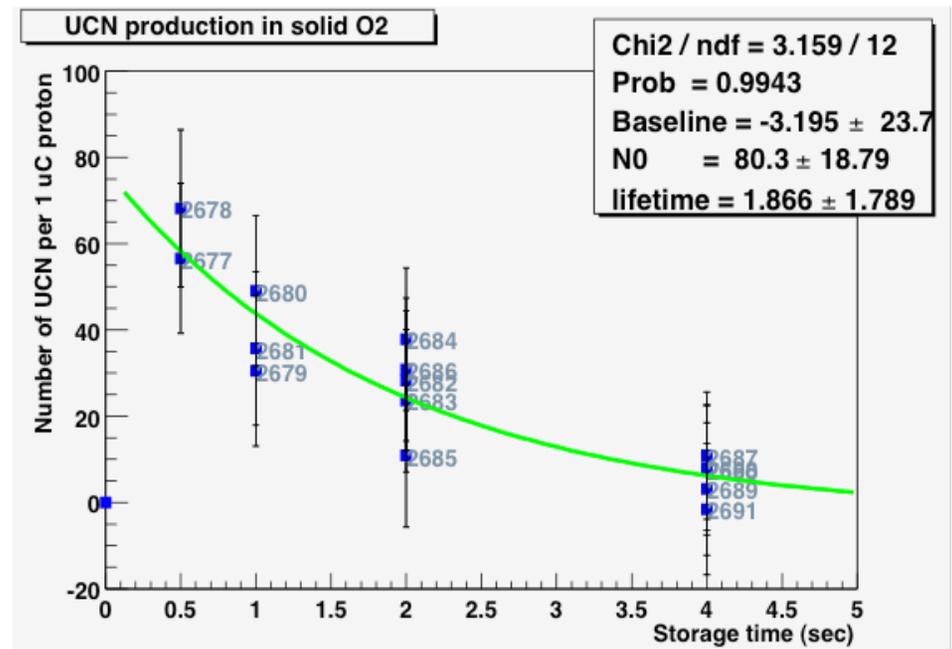
- Production rate
 - $P = 2.7 \times 10^{-8} \Phi_0$ (30K CN in S-O₂)
 - $P = 3.0 \times 10^{-8} \Phi_0$ (15K CN in S-O₂)
 - $P = 1.5 \times 10^{-8} \Phi_0$ (30K CN in S-D₂)
 - **Gain ~ 2 relative to S-D₂**
- Lifetime
 - 375 ms in S-O₂
 - 40 ms in S-D₂
 - **Gain ~ 10**
- Volume gain, (l)ⁿ, n= 1-3
 - $l_{\text{ucn}} = 380$ cm in S-O₂
 - $l_{\text{ucn}} = 8$ cm in S-D₂
 - **Gain ~ 50 - 10⁵**



Compared with S-D₂,
Gain > 1000 is possible !

1st experimental attempt with S-O₂ (2000, LANSCE) LANL UCN team

- Use the S-D₂ prototype source to test S-O₂
- 20 c.c. S-O₂ at 4.5K
- Preliminary results:
 - UCN are produced and bottled.
 - 1/5 UCN produced than from S-D₂ with the same condition
 - No distinct temperature dependence



- Limitation:
 - Diffusive solid oxygen film along the UCN guide all the way up to below the L-N₂ radiation shield (~ 1m).

Measurement of the UCN production efficiency of solid D₂ and comparison with the solid cryogenic materials CD₄ and O₂

Collaboration

F. Atchison, B. Blau, B. van den Brandt, T. Brys, M. Daum, P. Hautle, R. Henneck, S. Heule, M. Kasprzak, K. Kirch, A. Knecht, J. A. Konter, A. Pichlmaier, M. Wohlmuther, G. Zsigmond

(PSI)

K. Bodek, M. Kuzniak, J. Zejma (Jagiellonian University)

P. Geltenbort, C. Plonka (ILL)

A. Holley, A. R. Young (NCSU)

C.-Y. Liu, Y. Shin (IU)

C. L. Morris, A. Saunders, (LANL)

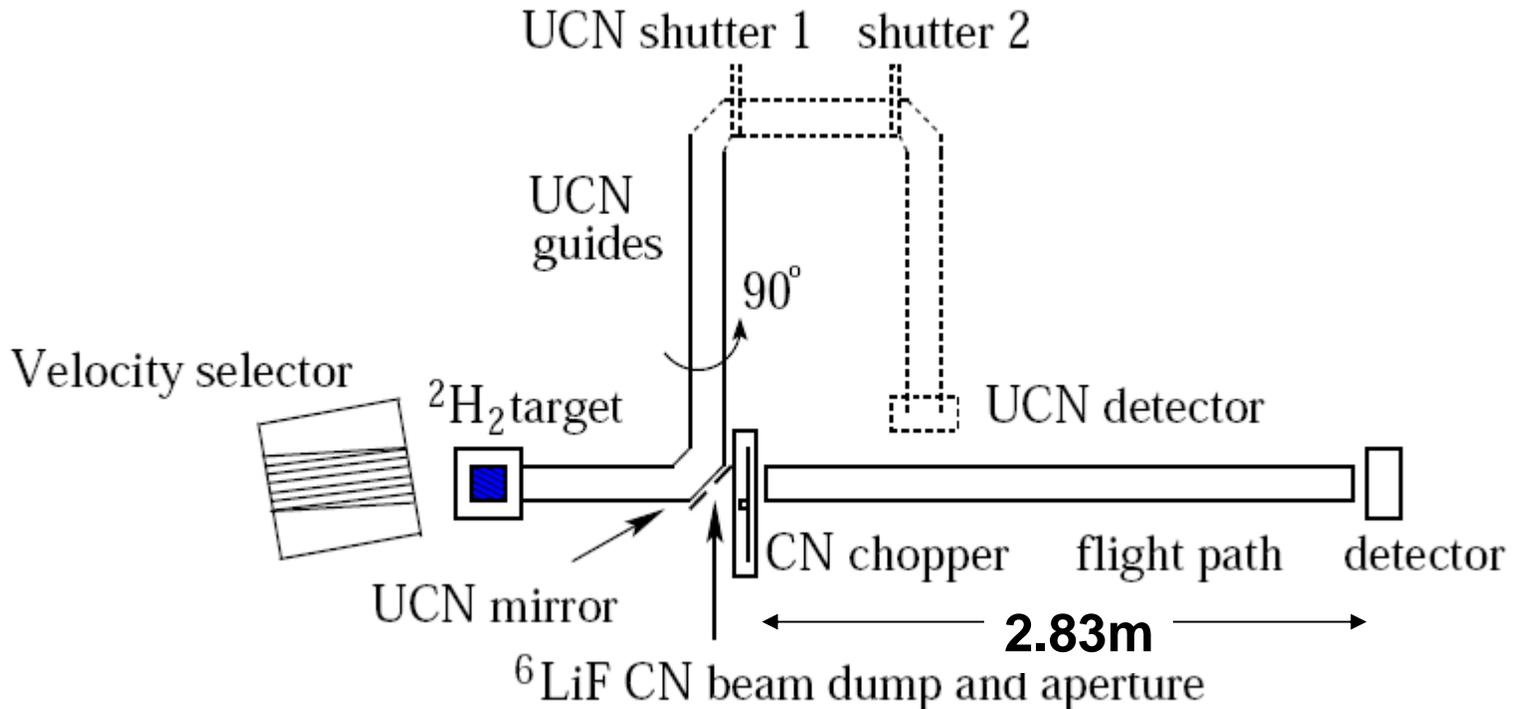
Y. Pokotilovski (JINR, Dubna)

D. Tortorella (TUM)

Experimental Setup at PSI (Oct. 2005)

F. Atchison, et. Al., Phys. Rev. C. 71, 054601 (2005)

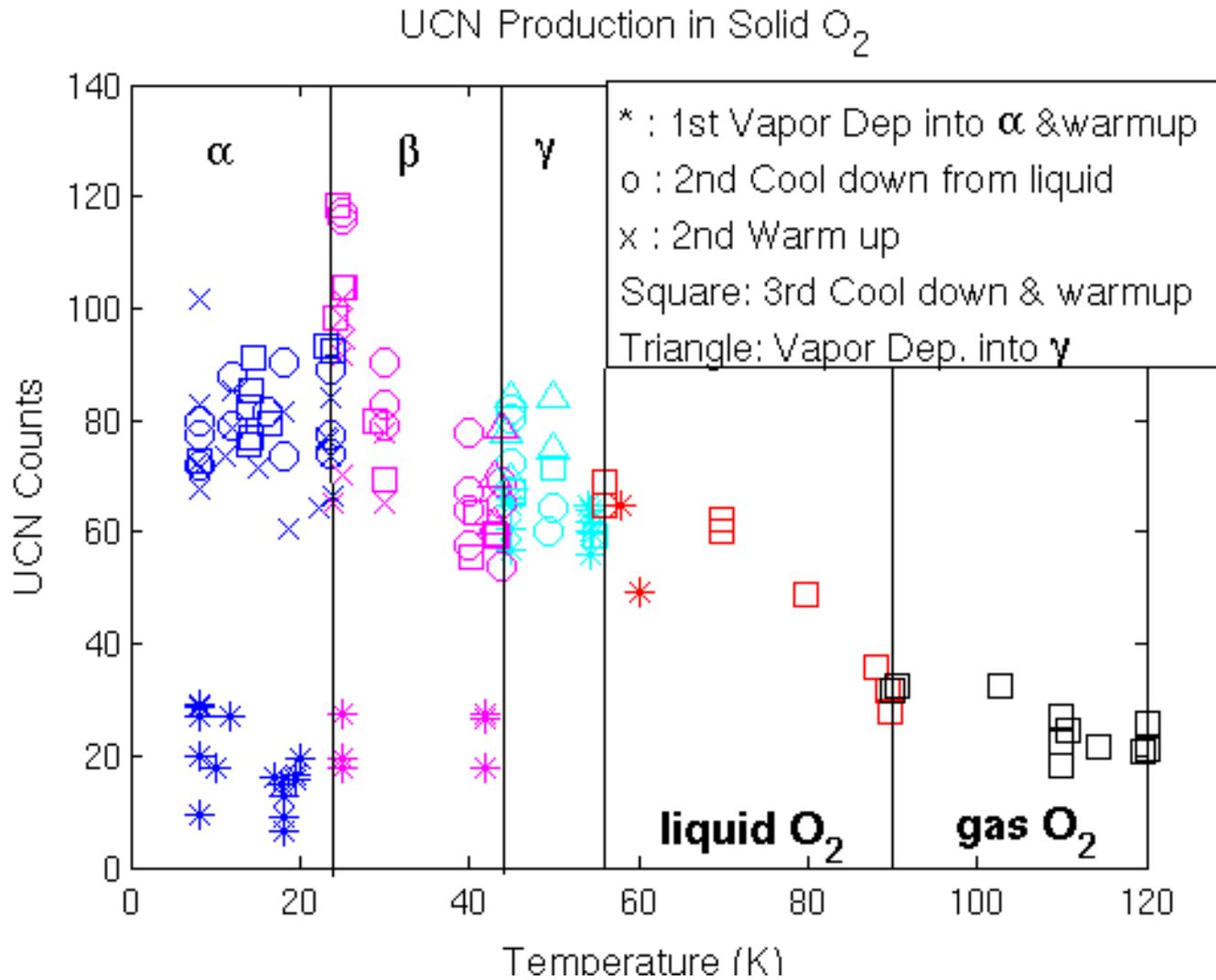
F. Atchison, et. Al., Phys. Rev. Lett, 99, 262502 (2007)



FunSpin beamline in SINQ

- $\Phi_{\text{CN}} = (4.5 \pm 1.0) \times 10^7 / \text{cm}^2 \cdot \text{s} \cdot \text{mA}$, with 1.2mA on SINQ target
- UCN count rate in the detector of 0.4/s, with a S/N ratio of 40 to 1.
- Similar count rate is expected using solid oxygen, assuming the same UCN extraction efficiency.

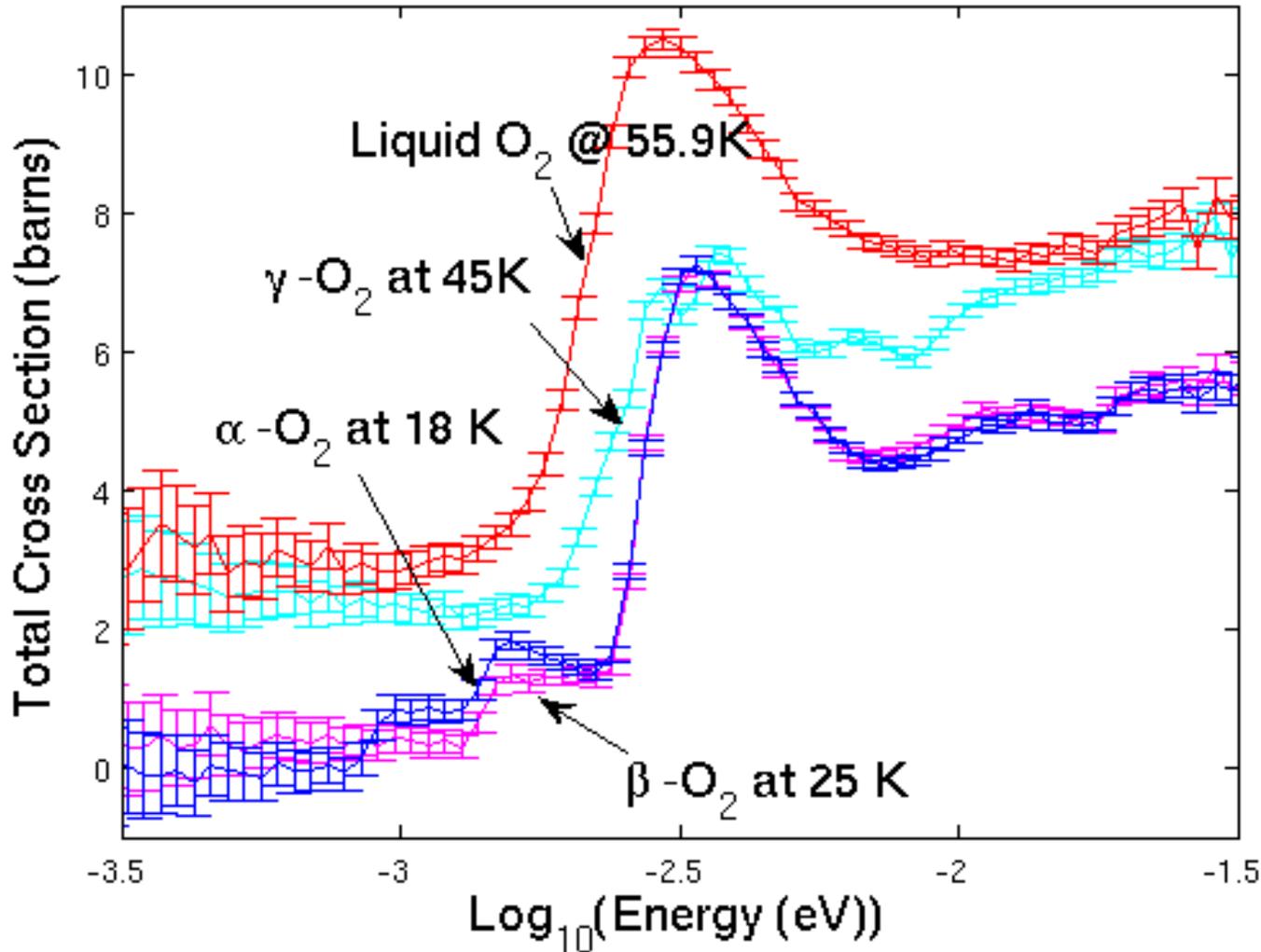
Results of UCN Production in Solid O₂ at PSI



- No superthermal temperature dependence.
 - unknown source of UCN loss.
- UCN yield is correlated with how the crystal is prepared.
- The UCN yield (best number) is ~ 3 times less than s-D2.
- A peak in the α - β phase transition (critical scattering¹⁶?)

Cold Neutron Transmission (TOF)

Cold Neutron Scattering in O₂

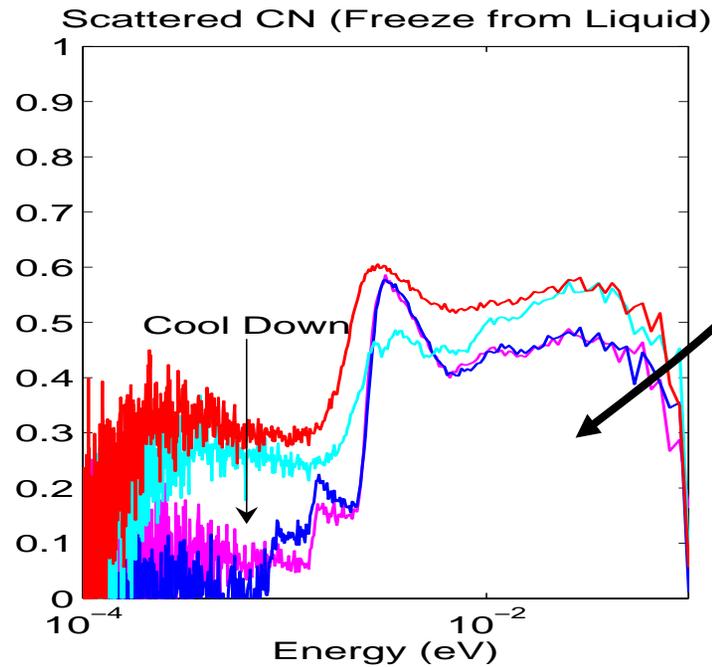
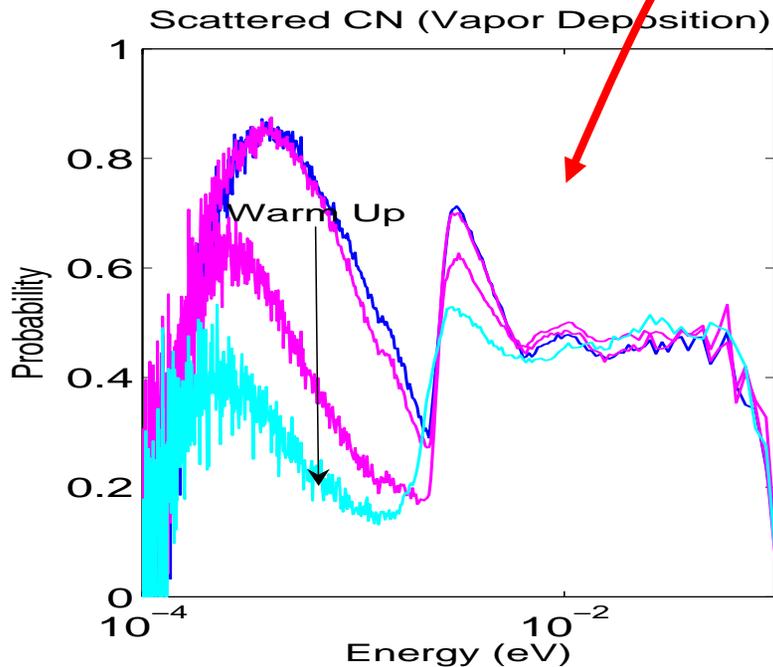
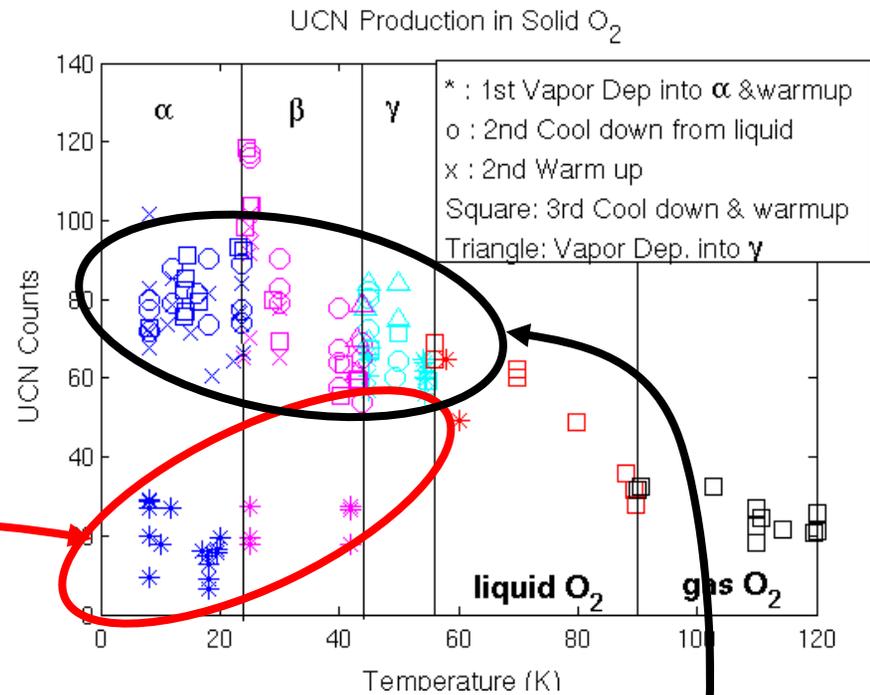


- Less scattering compared with D₂.
- Bragg edges
- Additional Bragg peak in α-phase. ⇒ the presence of a magnetic ordering.

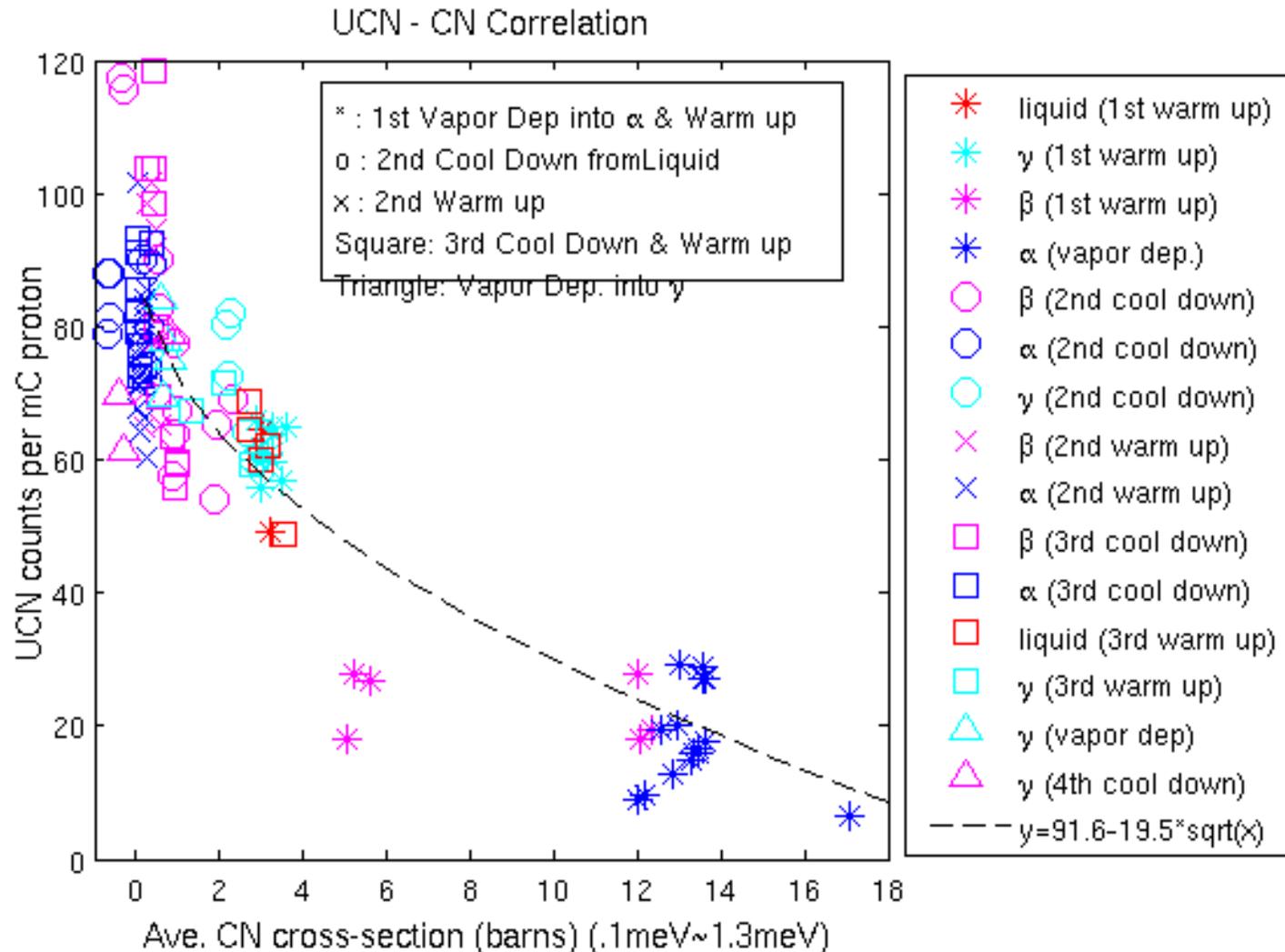
UCN Production vs. CN Transmission

UCN yield is strongly correlated with CN scattering.

Material: solid O_2



Correlation of UCN production vs CN scattering



UCN production was not effected by temperature or phase.

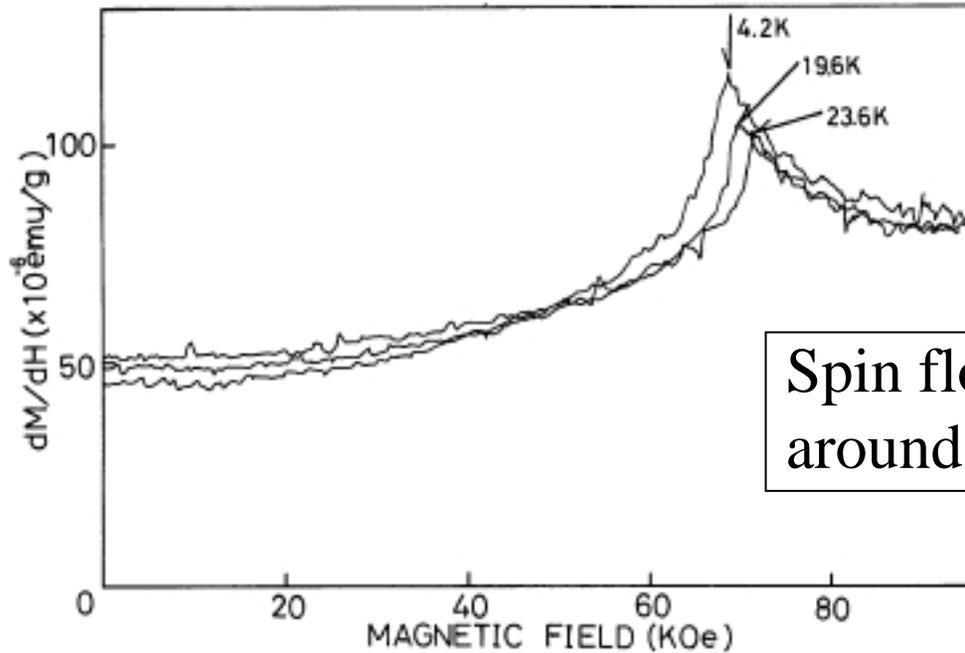
Something (other than downscattering) is dominating the yield of UCN.

Sources of UCN Loss in Solid O₂

- Elastic scattering due to cracks & voids (Hard to estimate)
- Incoherent elastic scattering
 - Nuclear: zero
 - Magnetic: non-zero for paramagnetic phase (liquid, γ , β); zero for coherent phase (α).
- Magnon/Phonon upscattering
 - Temperature dependent
 - 20K: ~8 barns
 - 10K: ~1.5 barns
 - However, we did not see a strong temperature dependence on UCN yield and CN scattering ???
- Upscattering due to rotational states transitions at high temperatures
 - Only odd rotational states are present. (ground state: $J=1$)
 - Libron mode

1st major challenge: understand and mitigate sources of loss

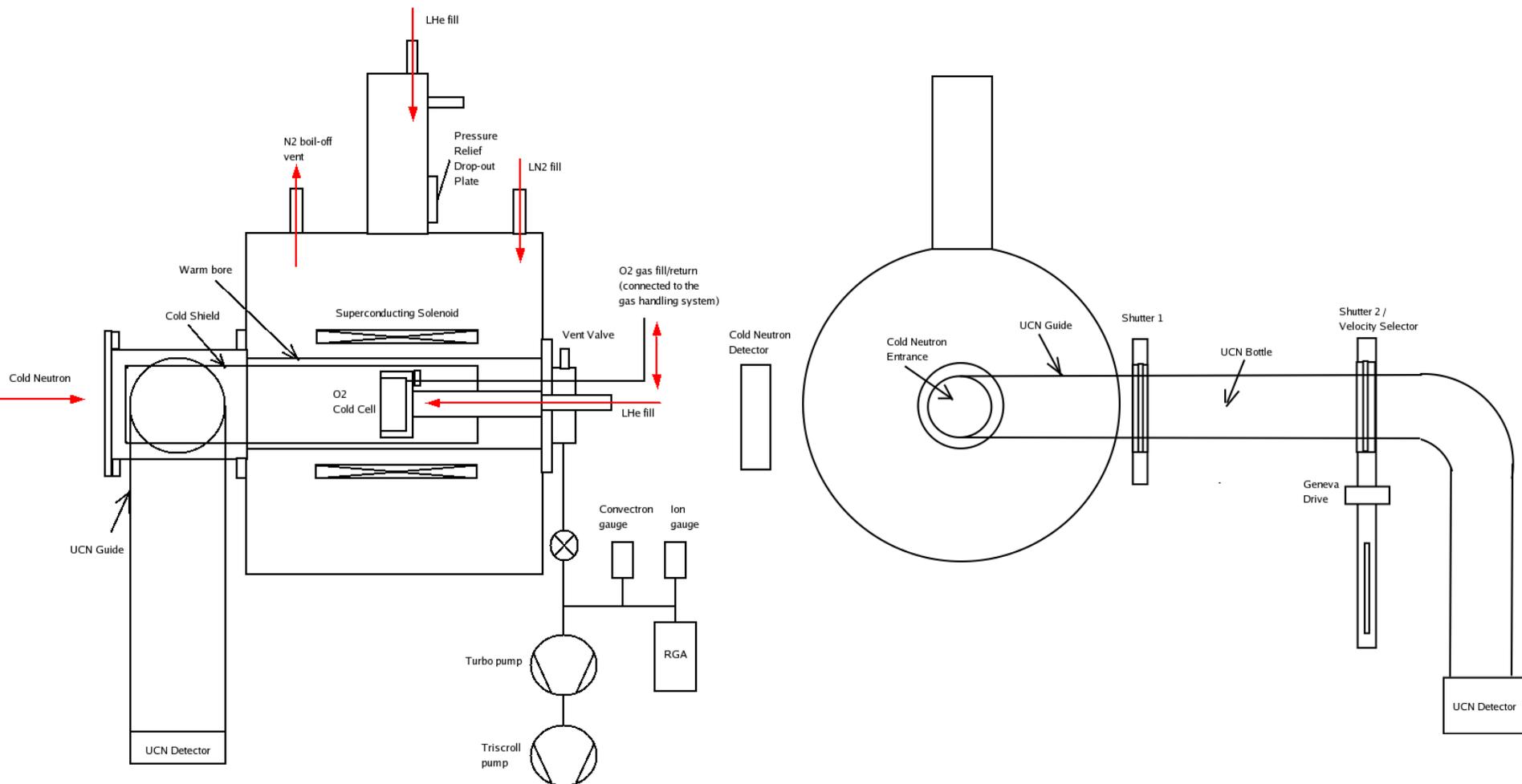
Probe the Magnon Mechanism using a B field



C. Uyeda et al., J. Phys. Soc. Jpn. 54, 1107 (1985)

- An external magnetic field to perturb the magnon dispersion curve
 - Change the density of states. **An unique feature of oxygen!**
 - Optimize UCN production.
- Definitive demonstration of the magnon mechanism.

LANSCE (FP12), 2007-2008 UCN Source Cryostat



Side View

Front View

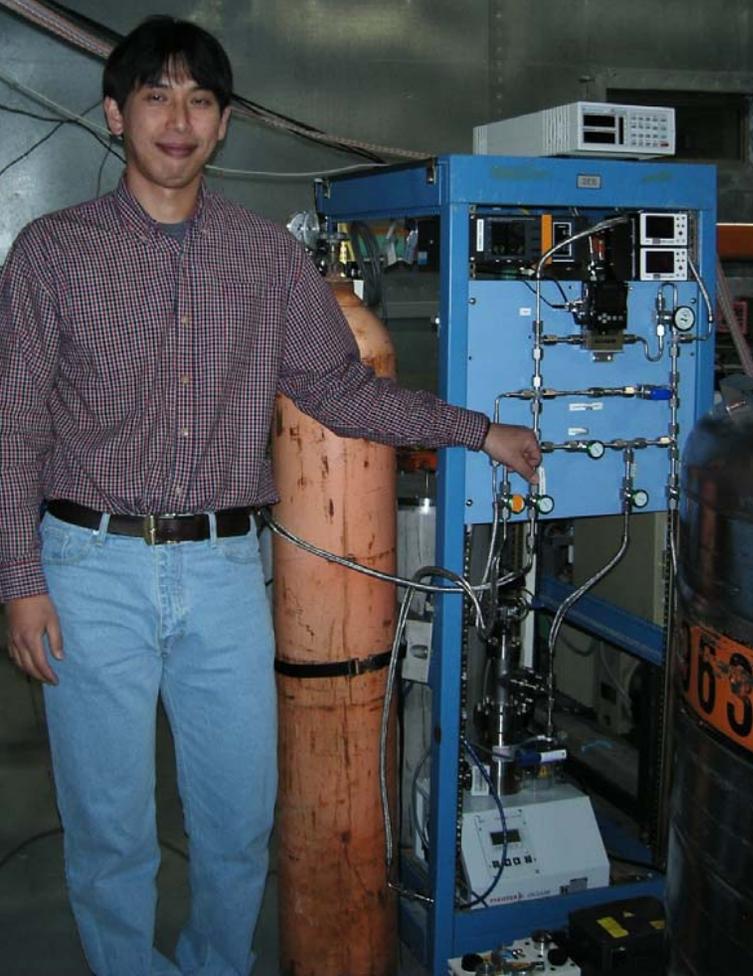
Superconducting Solenoid & Solid O₂ Target Cryostat

SC solenoid Cryostat

Flow He Cryostat
for O₂ target

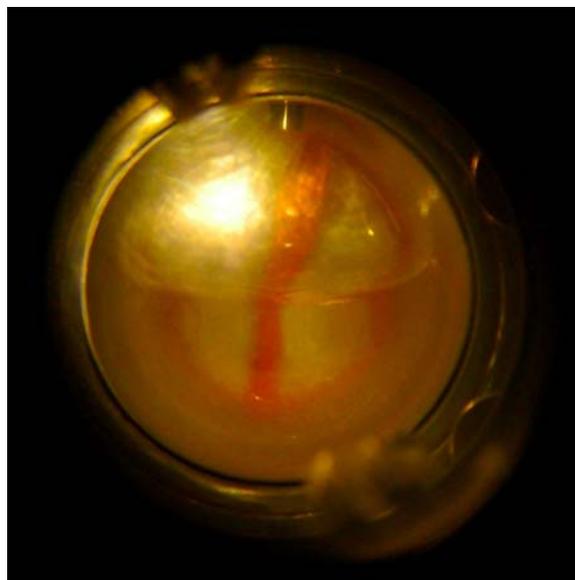
5.5T with
90 Amp

SC Solenoid Power
Supply



Y. Shin

O₂ Gas Handling System (all VCR)

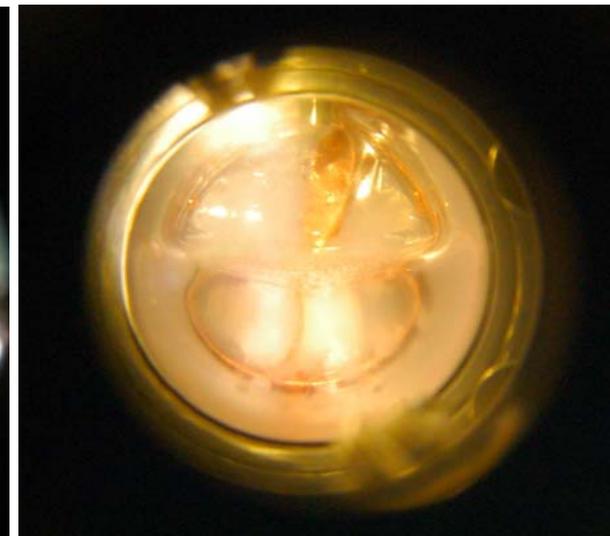


• Optical cell

beta-gamma phase transition
(slow cool-down
~0.017K/min)

beta phase
(slow vapor deposition)

beta phase
(slow cool down)



O₂ UCN Source Development Program

- Previous measurements
 - LANL
 - PSI
- 2007-2008 (July – October)
 - Lujan Center (ER2) Flight Path 12
 - UCN production under B field
 - CN TOF transmission
 - UCN gravity spectrometer / Velocity filter
 - PHAROS: one week beam time to measure S(alpha, beta) in solid oxygen under high field.
- **UCN Source coupled to LENS at IUCF.**

Low Energy Neutron Source (LENS) at IUCF

D. Baxter, H. Kaiser, C. M. Lavelle, M. Leuschner, W. R. Lozowski,
N.B. Remmes, M.W. Snow, T. Rinckel, P.E. Sokol

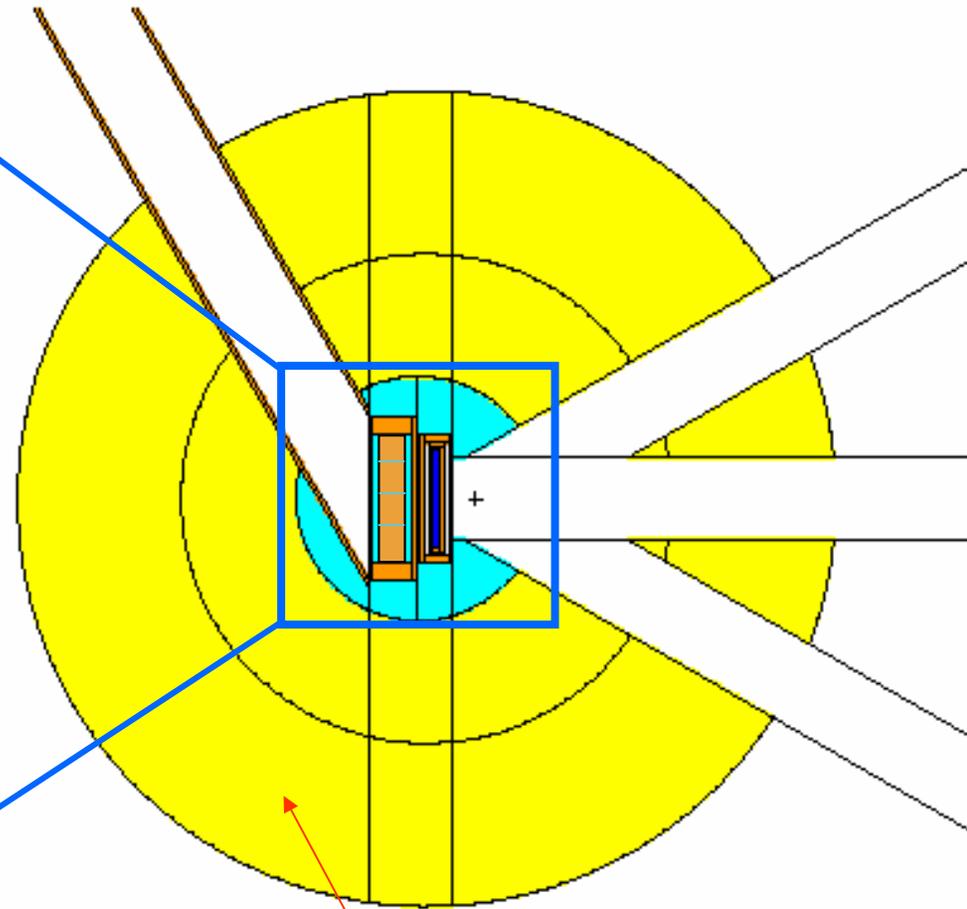
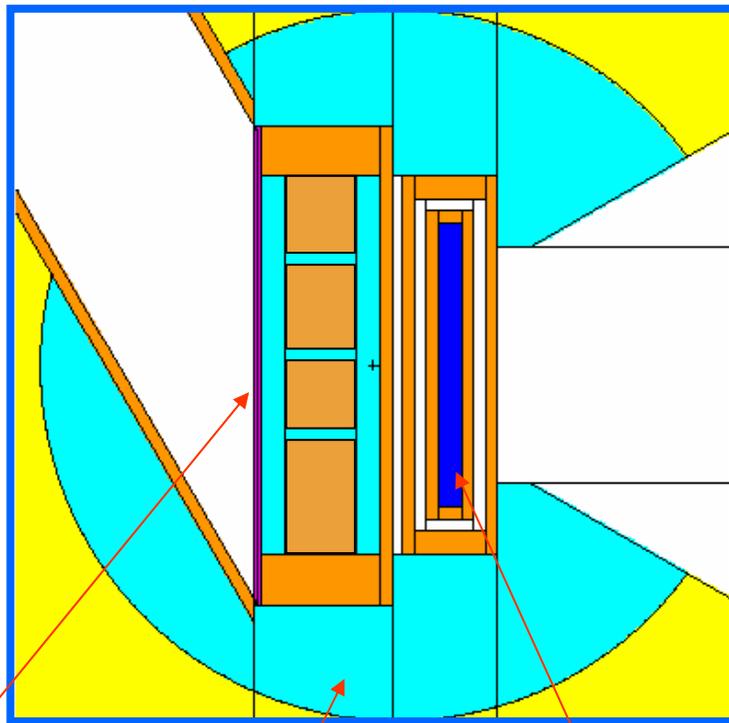


Proton Linac (13MeV)

1st Target Station: NRE

Target/Moderator/Reflector (TMR) Assembly

${}^9\text{Be}(p,n){}^9\text{B}$ reaction



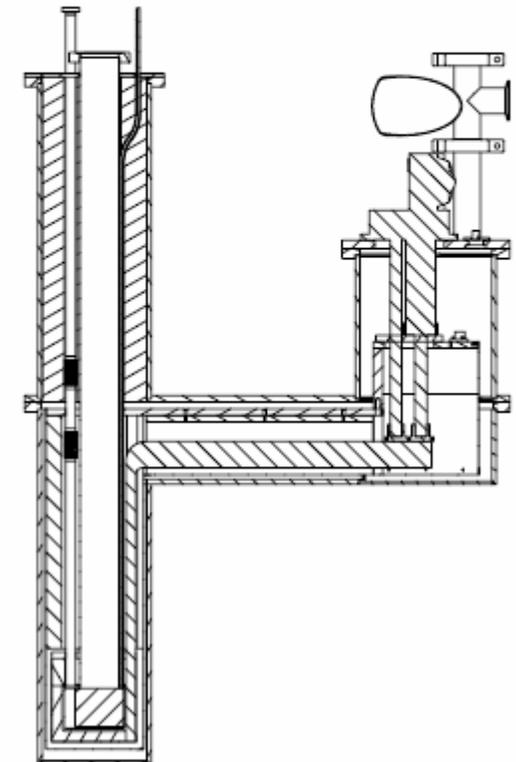
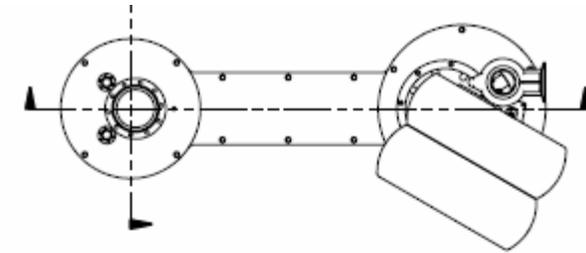
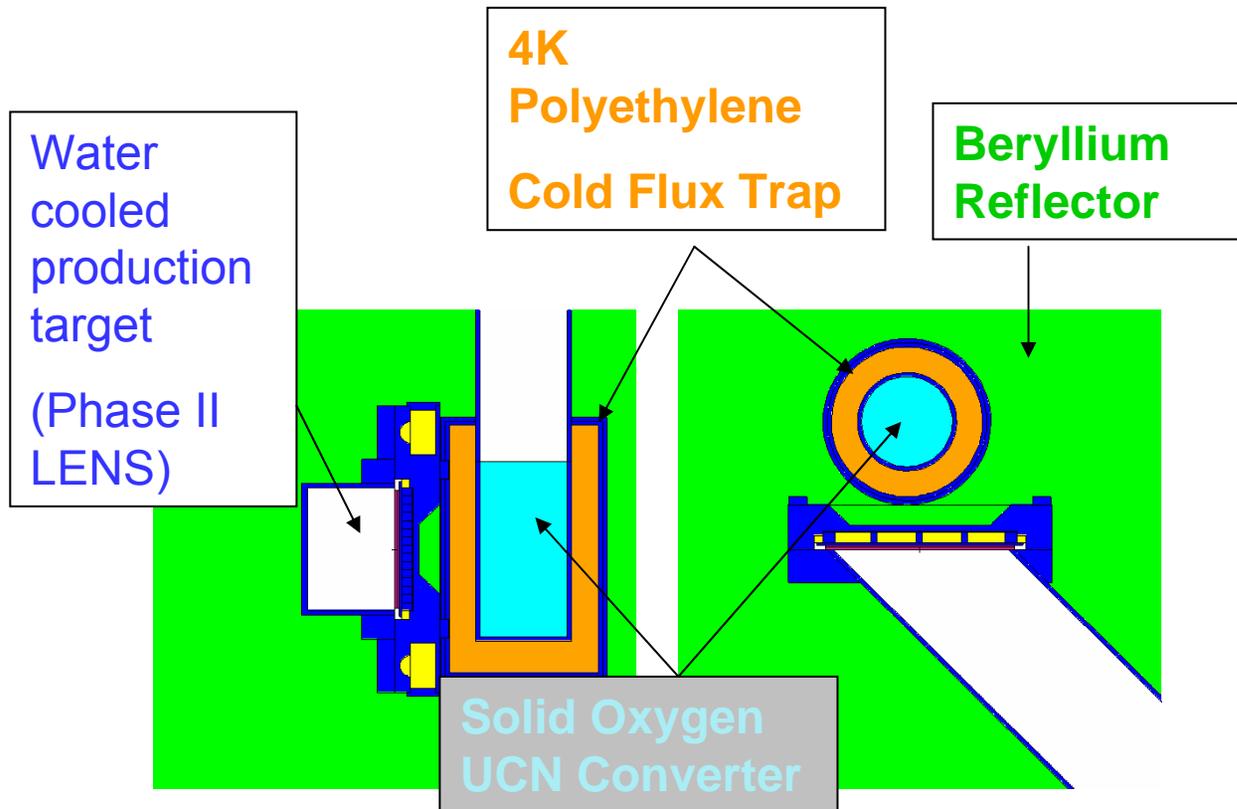
Thin beryllium
production target

inner reflector – water

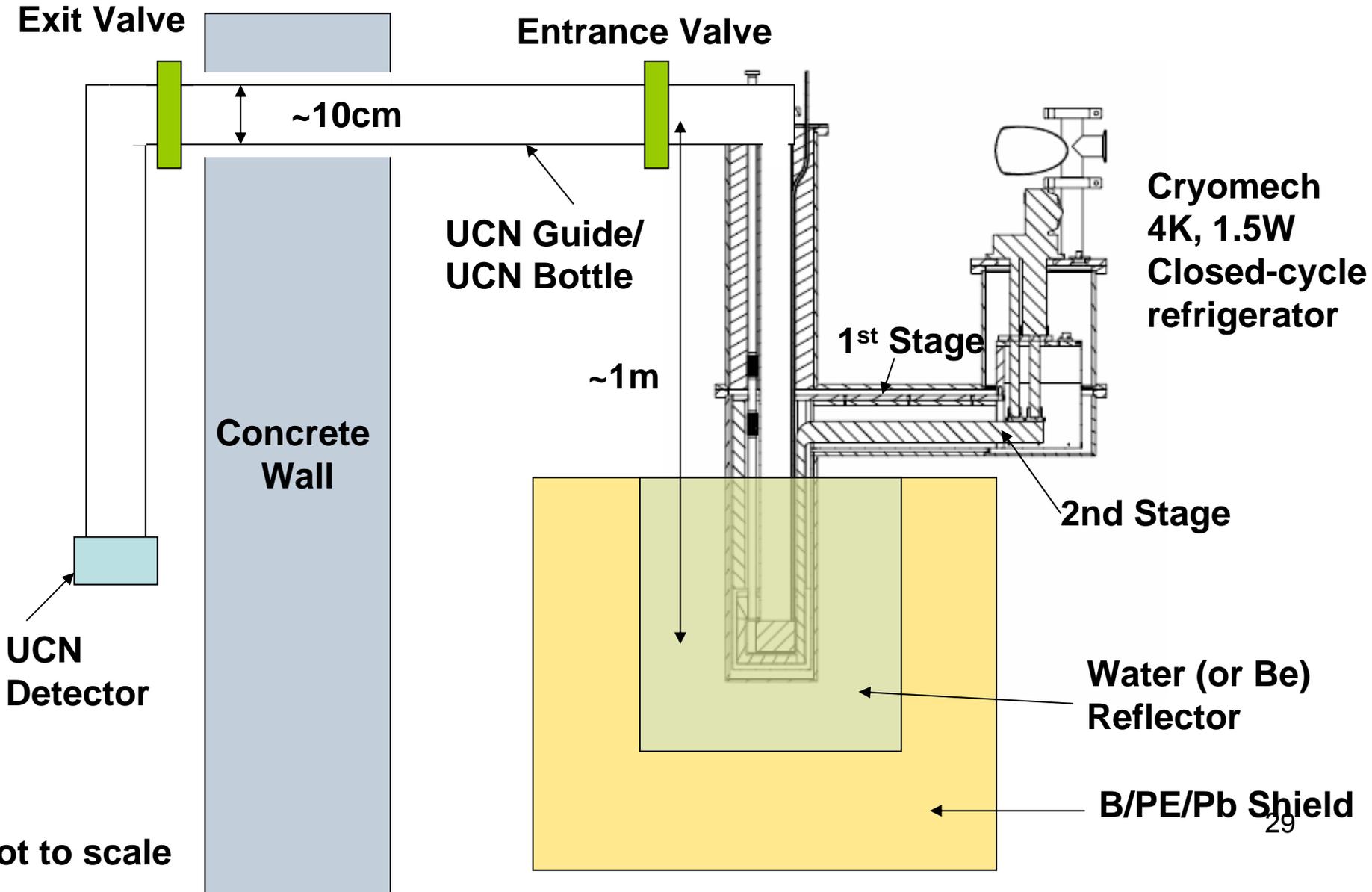
Methane moderator

Outer shielding – lead
and poly layers

Kernel of the UCN Module



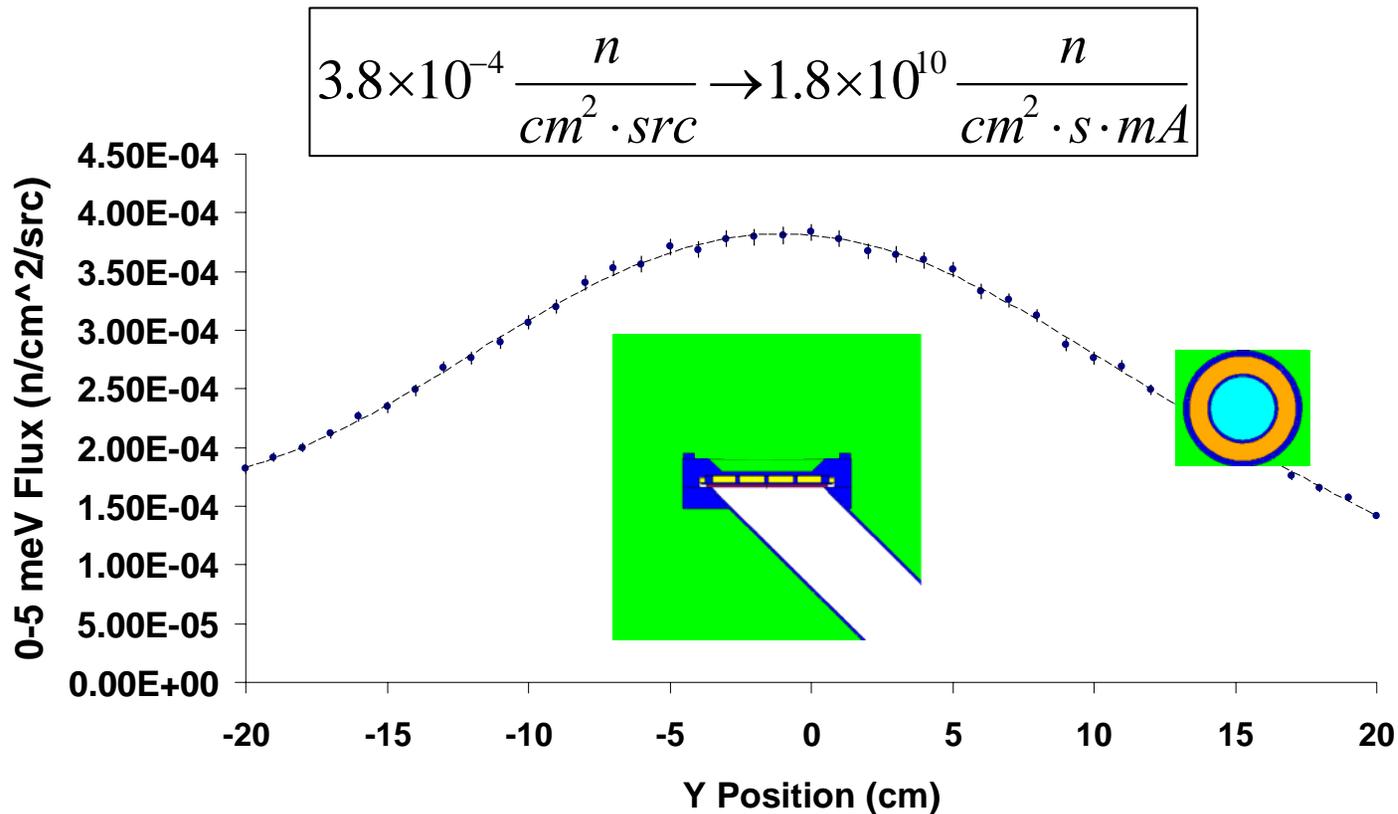
UCN Module at LENS



Using a 2.0 cm thick trap, 1000 cc solid oxygen source we can model the volume average cold flux in the oxygen as a function of position. 1 cm left of center is optimal.

The peak cold flux is

MCNP by C. Lavelle



Solid Oxygen

UCN Conversion Rate, P:

Calculation based on inelastic magnetic scattering

$$P \approx 3 \times 10^{-8} \text{ cm}^{-1}$$

0-5 meV Neutron Flux, Φ_{CN} (13meV, Be reflector)

MCNP simulation validated by the LENS cold flux measurements

$$\Phi_{\text{cn}} \approx 1.8 \times 10^{10} \frac{\text{cn}}{\text{cm}^2 \cdot \text{s} \cdot \text{mA}}$$

UCN Density in source:

$$P \times \Phi_{\text{CN}} \times \tau$$

τ : escape time $\sim 30\text{ms}$

$$\rho_{\text{ucn}} \approx 30 \text{ ucn} / \text{cm}^3 \cdot \text{mA}$$

UCN Current output:

$$P \times \Phi_{\text{CN}} \times V$$

V: source volume ~ 1 liter

$$\bullet \text{ Be} \\ N_{\text{ucn}} \approx 1.1 \times 10^6 \text{ ucn} / \text{s} \cdot \text{mA}$$

$$\bullet \text{ Water} \\ N_{\text{ucn}} \approx 6.4 \times 10^5 \text{ ucn} / \text{s} \cdot \text{mA}$$

Heat Load (MCNP results)

Cell	Photon Heat (W)	Neutron Heat (W)	Target Photon Heat (W)	Total (W)	
sO2	0.20	0.08	0.12	0.39	
sO2 Al	0.09	0.01	0.04	0.15	0.54
Poly	0.39	1.58	0.17	2.13	
Poly Al	0.20	0.03	0.09	0.32	
Guide	0.07	0.00	0.01	0.09	2.54

With 1mA, 13MeV proton current on Be target

We expect

UCN density ~ 30 ucn/cc in the s-O₂.

UCN fluence: 6×10^5 ~ 1×10^6 ucn/s from a 1 liter s-O₂.

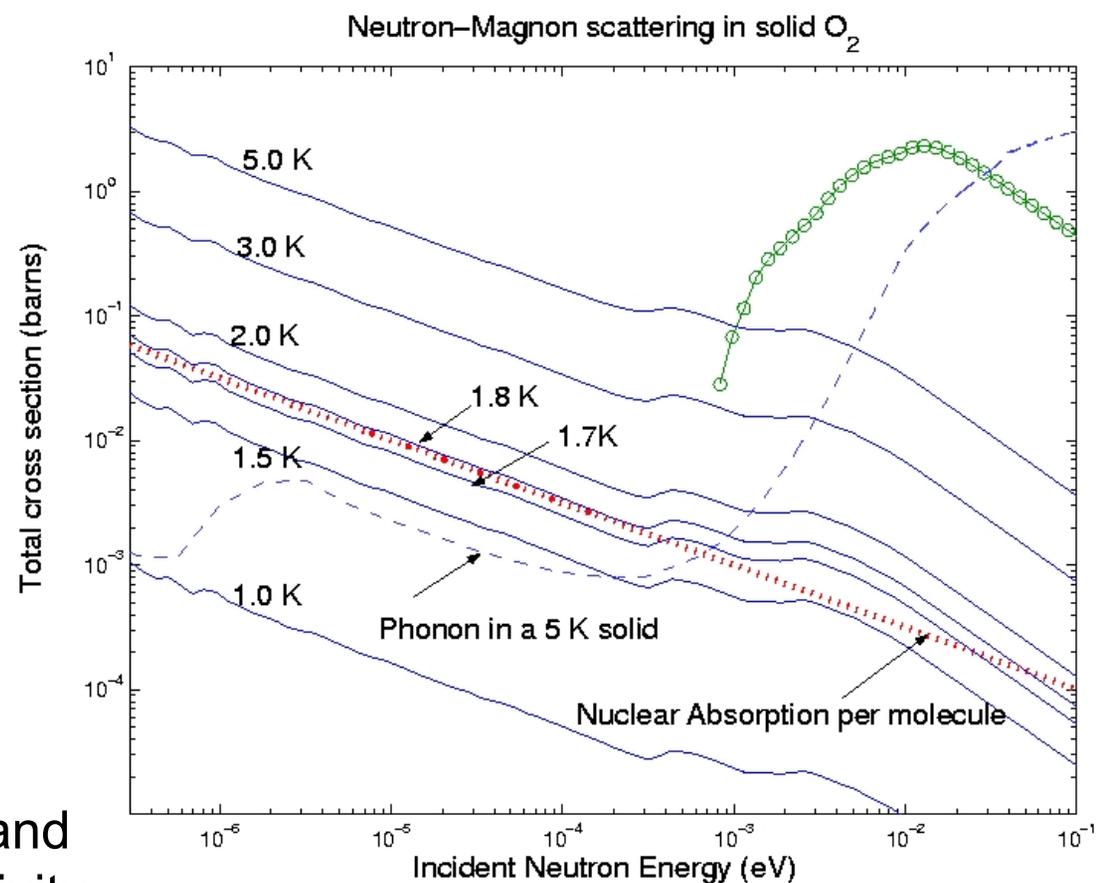
Challenges

- **1.8 K cryogenic.**

- Larger gamma heating and smaller thermal conductivity than S-D₂ ⇒ challenges on cryogenic engineering
- Requires a fast thermal break (50K to 2K) over a few cm.

- **Shortened UCN mean free path**

- Polycrystalline sample formation
- Ozone formation ⇒ additional incoherent scattering, resulting in a reduced mean free path. (Low radiation level at LENS helps.)



Collaborators

- **Indiana University**
 - **Chen-Yu Liu (PI)**
 - **Yun Chang Shin (Grad. Student)**
 - **Chris Lavelle (Postdoc)**
 - **Bill Lozowski (Tech)**
 - **Walt Fox (Designer)**
- **North Carolina State University**
 - **Albert Young**
- **Los Alamos National Laboratory**
 - **Andy Saunders, Chris Morris, Mark Makela**