A Solid Oxygen based Ultra-cold Neutron Source at IUCF

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Outline

- What are Ultra-cold Neutrons (UCN)?

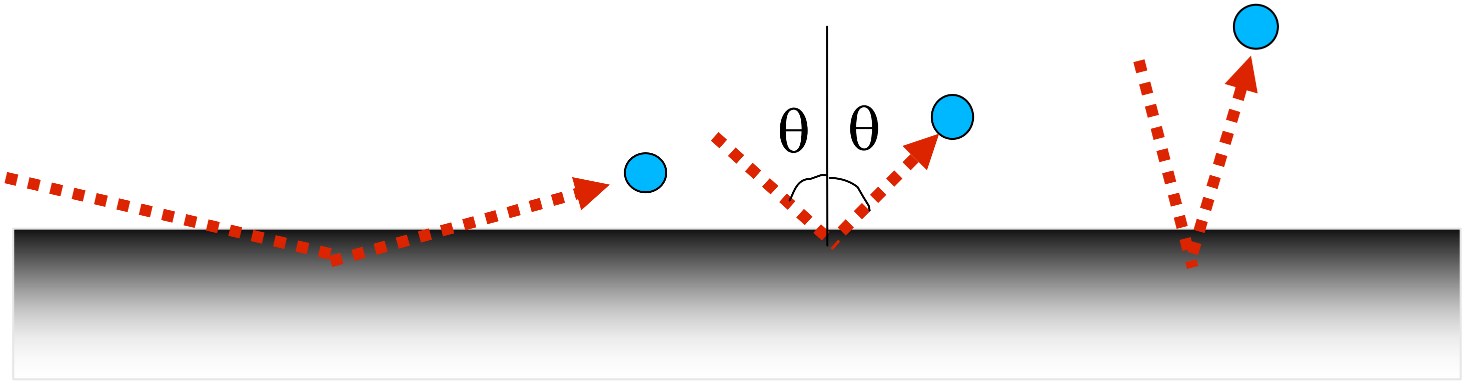
- How are UCN useful?
  - Neutron physics with UCN
    - Neutron beta-decay
    - Neutron EDM search
    - **n-nbar oscillation**

- How to make a lot of them?
  - Superthermal UCN production
    - Solid D_2
    - **Solid O_2**

UCN

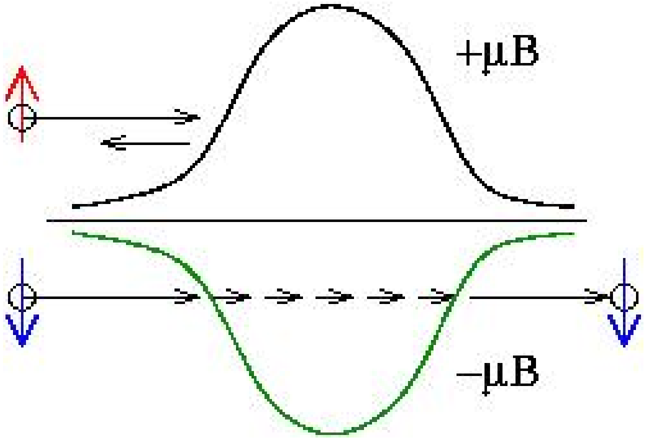
- E < 335 neV (Ni^{58})
- T < 4 mK
- Velocity < 8m/s
- $\lambda > 500$ Å

$$V = \frac{2\pi\hbar^2}{m_n}\overline{\sum_i b_i\delta(r - r_i)} = \frac{2\pi\hbar^2}{m_n} b_{coh}\rho$$



Why UCN?

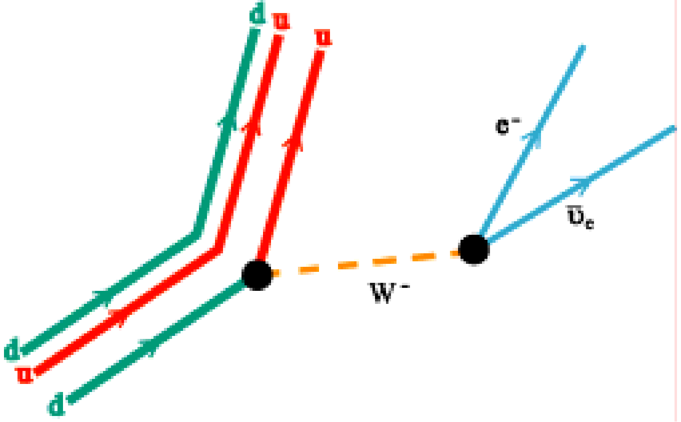
UCN have advantages over higher energy neutrons (cold neutrons):



- **UCN can be confined in a trap**
  - Copper wall ~ B=2.8 T ~ h=1.7m
- **Low background**
- **Long storage time**
  - UCN can be stored up to the β-decay lifetime, a relatively long coherence time of measurements (for particle physics experiments).
- **100% neutron polarization**
  - Provide motivation to shift from cold neutron beams to UCN for β-decay angular correlation experiments and EDM experiments.

Clean, high precision experiments with reduced, well controlled systematic effects.

Neutron β-decay



Lifetime

- Cold Neutron beam experiments: $t_\beta = N_0 / \dot{N}_d$
  - Absolute measurements of the neutron number and the decay particle flux.
- Bottled UCN: $N(T) = N_0 e^{-T/t_\beta} \Rightarrow t_\beta = T \ln(N_0 / N(T))$
  - Ratio of the neutrons stored for different periods. It is a relative measurement.
  - Material bottle -- Mampe (887.6 ± 3 s)
    - Wall loss depends strongly on the UCN spectrum.
    - Systematically limited.
  - Magnetic bottle -- hexapole bottle (876.7 ± 10 s), NIST bottle.

Neutron measurements which address fundamental particle physics issues

- **Neutron β-decay lifetime and angular correlations**

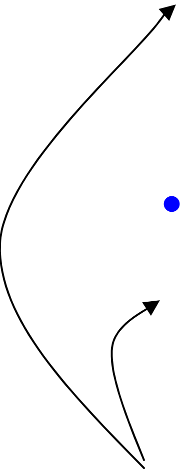
  test the **V-A theory** and place direct constraints on extensions to **charged current sector** of the standard model.

- **Permanent electric dipole moment (EDM) search**

  T reversal symmetry & CP violation extensions to the standard model.

- **N-Nbar oscillation search**

  place useful limits on **(B-L) violating** processes.



Motivated by the observed baryon asymmetry of the universe.

n→nbar (ΔB=2) Theoretical Motivations

- Baryon Asymmetry of the Universe (BAU)
  - **Sakharov Criteria**
    - **Baryon Number Violation**
    - CP & C violation (EDM search)
    - Departure from Thermal Equilibrium
- Unification of particles and interactions.
  - Processes predicted by some GUT models.
  - Proton decay. ΔB=1 (= ΔL)

$$p \to e^{+}\pi^{0} > 5.7 \cdot 10^{33}\ years$$

$$p \to \bar{\nu}K^{+} > 2.0 \cdot 10^{33}\ years$$

- In nucleon disappearance, the conservation of angular momentum leads to the selection rule:
  - ΔB=± ΔL or | Δ(B-L)|=0,2
  - In SM, Δ(B-L)=0 always.
  - Δ(B-L)≠0 → ΔB=– ΔL or ΔB=2 or ΔL=2

$$n \to \bar{n} \qquad \Delta B = 2$$

$$p \to \nu\nu e^{+}\ \Delta B = -\Delta L$$

$$n \to \nu\nu\bar{\nu}\ \Delta B = -\Delta L$$

n→nbar Oscillation

Unkown mixing interaction

- Schrödinger equation

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix}\psi_n\\ \psi_{\bar{n}}\end{pmatrix}=\begin{pmatrix}E_n & \varepsilon\\ \varepsilon & E_{\bar{n}}\end{pmatrix}\begin{pmatrix}\psi_n\\ \psi_{\bar{n}}\end{pmatrix}\quad,\quad\begin{pmatrix}\psi_n(0)\\ \psi_{\bar{n}}(0)\end{pmatrix}=\begin{pmatrix}1\\ 0\end{pmatrix}$$

$$|\psi_{\bar{n}}(t)|^2=\frac{4\varepsilon^2}{\omega^2+4\varepsilon^2}\sin^2(\frac{1}{2}\sqrt{\omega^2+4\varepsilon^2}t/\hbar)$$

$$\omega=(E_n-E_{\bar{n}})=(m_n+\frac{p^2}{2m_n}+V_n)-(m_{\bar{n}}+\frac{p^2}{2m_{\bar{n}}}+V_{\bar{n}})$$

- Transition Probability: (if ωt <<1)

$$P_{n\to\bar{n}}(t)=\psi_{\bar{n}}(t)^2=\varepsilon^2\cdot(t/\hbar)^2=\left(\frac{t}{\tau_{n\bar{n}}}\right)^2 \qquad \tau_{n\bar{n}}=\frac{\hbar}{\varepsilon}$$

Suppression of n→nbar transition

$$|\psi_{\bar{n}}(t)|^2 = \frac{4\varepsilon^2}{\omega^2 + 4\varepsilon^2}\sin^2\left(\frac{1}{2}\sqrt{\omega^2 + 4\varepsilon^2}\,t/\hbar\right)$$

- Free neutron in a magnetic field

$$\omega = (E_n - E_{\bar{n}}) = \left(m_n + \frac{p^2}{2m_n} + V_n\right) - \left(m_{\bar{n}} + \frac{p^2}{2m_{\bar{n}}} + V_{\bar{n}}\right) = 2\mu \cdot B$$

  - **Under earth field (0.5 gauss), 2μHB=6×10^{-12}eV**
  - $\varepsilon_{n\bar{n}} = \dfrac{\hbar}{\tau_{n\bar{n}}} < 10^{-23}eV$ with $\tau_{free} > 1.2\times10^{8}$ s

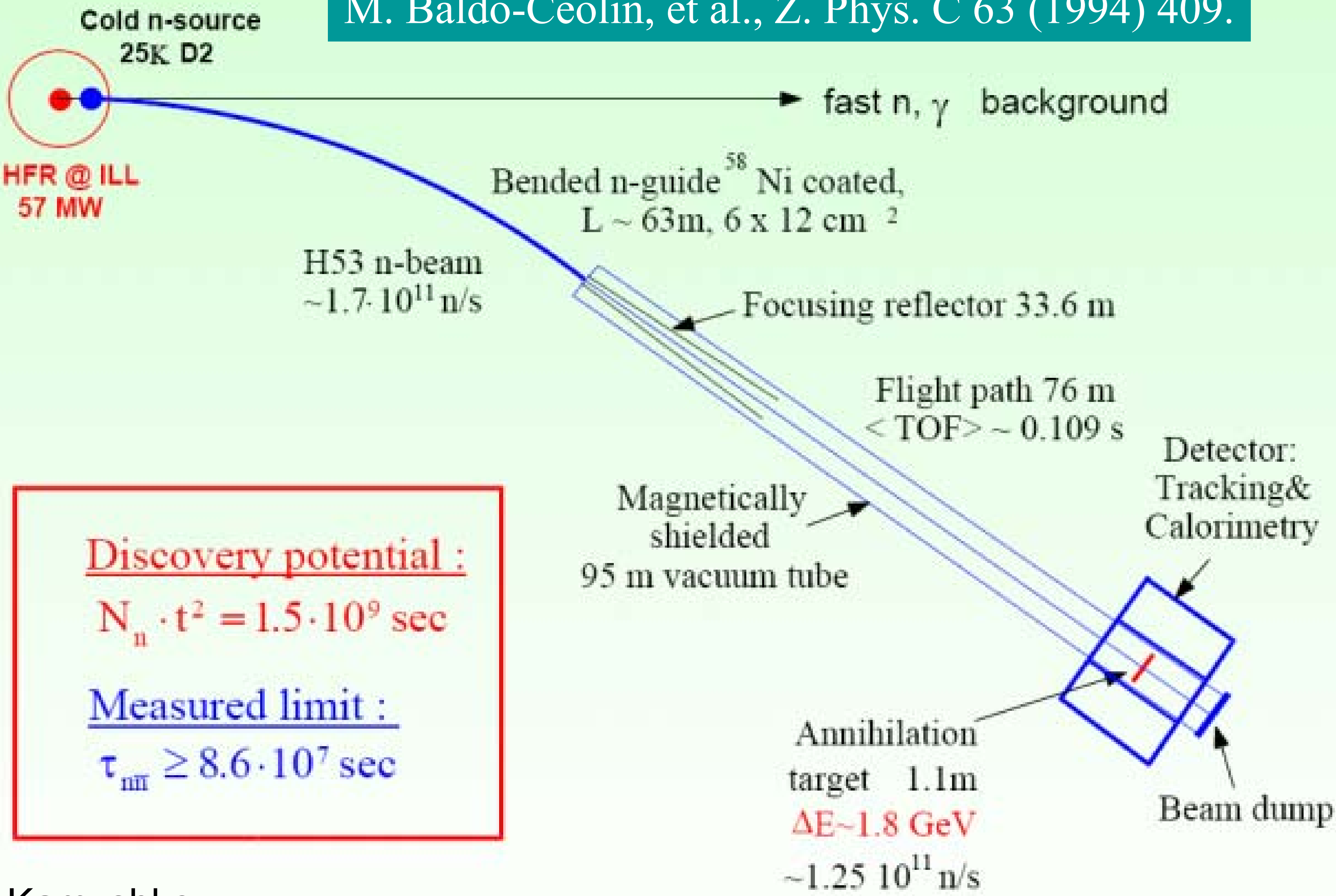
$$|\psi_{\bar{n}}(t)|^2 = \frac{4\varepsilon^2}{\omega^2}\sin^2(t/\tau_{Larmor}) = 10^{-23}\sin^2(t/2\times10^{-4})$$

- To measure $\tau_{free} > 1.2\times10^{8}$ s, the magnetic field has to be as small as 0.5×10^{-11}gauss!
- For the neutron time-in-flight t=0.1s,
  - B < 5 mgauss.

$$\varepsilon_{n\bar{n}} = \frac{\hbar}{\bar{t}} < 10^{-14}eV$$

Schematic layout of Heidelberg - ILL - Padova - Pavia $n\bar{n}$ search experiment at Grenoble 89-91

M. Baldo-Ceolin, et al., Z. Phys. C 63 (1994) 409.



Cold n-source
25K D2

HFR @ ILL
57 MW

fast n, γ background

Bended n-guide ^{58}Ni coated,
L ~ 63m, 6 x 12 cm ^{2}

H53 n-beam
~$1.7\cdot 10^{11}$ n/s

Focusing reflector 33.6 m

Flight path 76 m
< TOF> ~ 0.109 s

Magnetically
shielded
95 m vacuum tube

Detector:
Tracking&
Calorimetry

Annihilation
target 1.1m
ΔE~1.8 GeV
~$1.25\ 10^{11}$ n/s

Beam dump

Discovery potential :

$$N_n \cdot t^2 = 1.5 \cdot 10^9 \text{ sec}$$

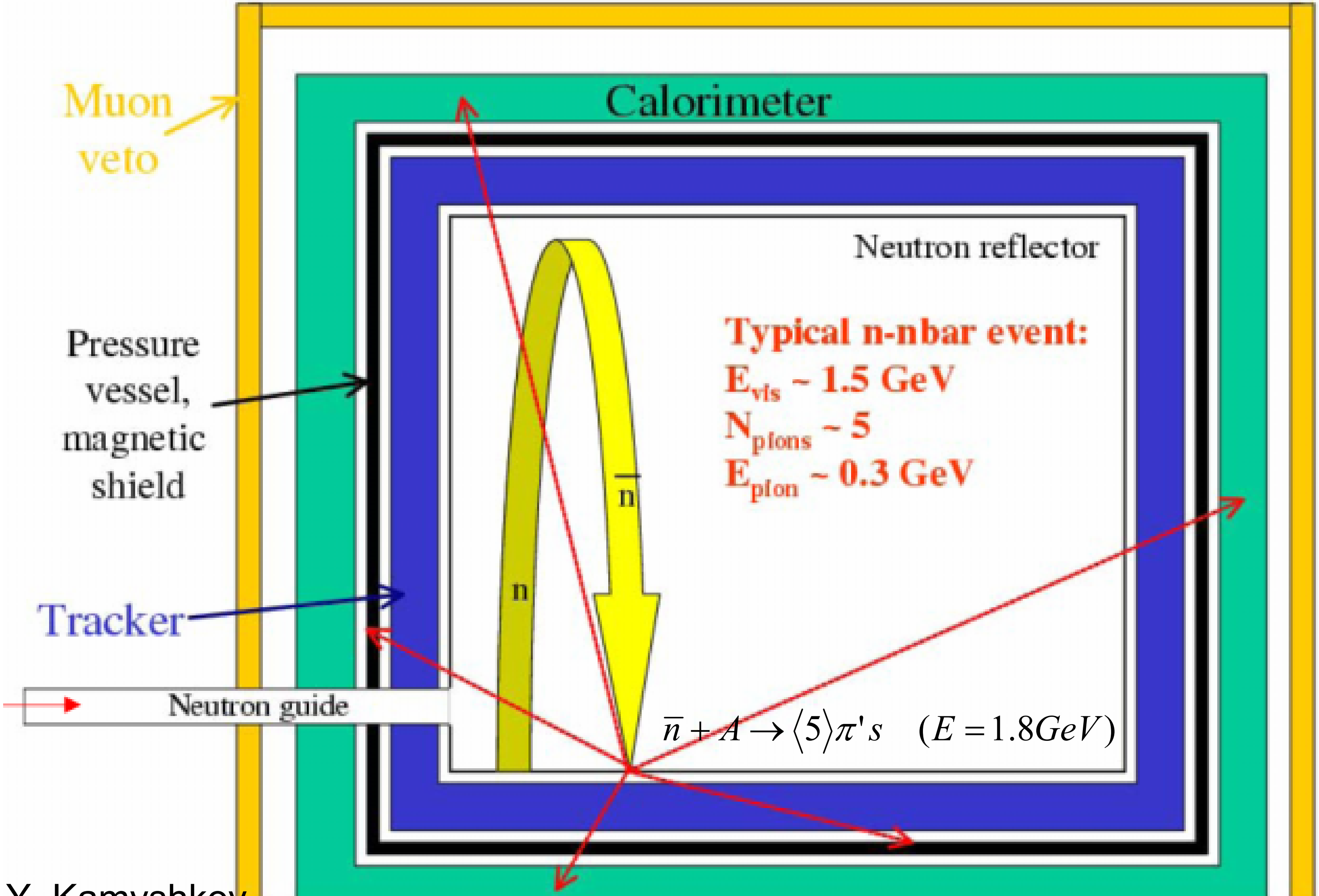
Measured limit :

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

Y. Kamyshkov

Typical Detector for the UCN N→Nbar Experiment

Typical detector size:
height 2.5 m
diameter 5 m



Typical n-nbar event:
E_{vis} ~ 1.5 GeV
N_{pions} ~ 5
E_{pion} ~ 0.3 GeV

$$\bar{n} + A \rightarrow \langle 5 \rangle \pi' s \quad (E = 1.8 GeV)$$

Y. Kamyshkov

Figure of Merit

- Probability of n→nbar event in free neutron exp:

$$N \cdot P = (\dot{N}_{cn} T) \cdot \left(\frac{\bar{t}}{\tau_{n\bar{n}}} \right)^2 \le 1 \quad \Rightarrow \quad \tau_{n\bar{n}} \ge \left(\sqrt{\dot{N}_{cn} T} \right) (\bar{t}) \varepsilon_{ff}$$

$$\tau_{n\bar{n}} > (\sqrt{1.25 \cdot 10^{11} \cdot 2.4 \cdot 10^{7}}) \cdot 0.109 \cdot 0.48 = 8.6 \times 10^{7} s$$

- Probability of UCn →UCnbar event:
  - Every wall collision destroy the phase coherence and reset the experiment.

$$N \cdot P = (\dot{N}_{ucn} T) \cdot \left(\frac{\bar{t}}{\tau_{n\bar{n}}} \right)^2 \cdot \left(\frac{\tau_{ucn}}{\bar{t}} \right) \le 1 \quad \Rightarrow \quad \tau_{n\bar{n}} \ge \left(\sqrt{\dot{N}_{ucn} T} \right) \sqrt{\tau_{ucn} \bar{t}} \; \varepsilon_{ff}$$

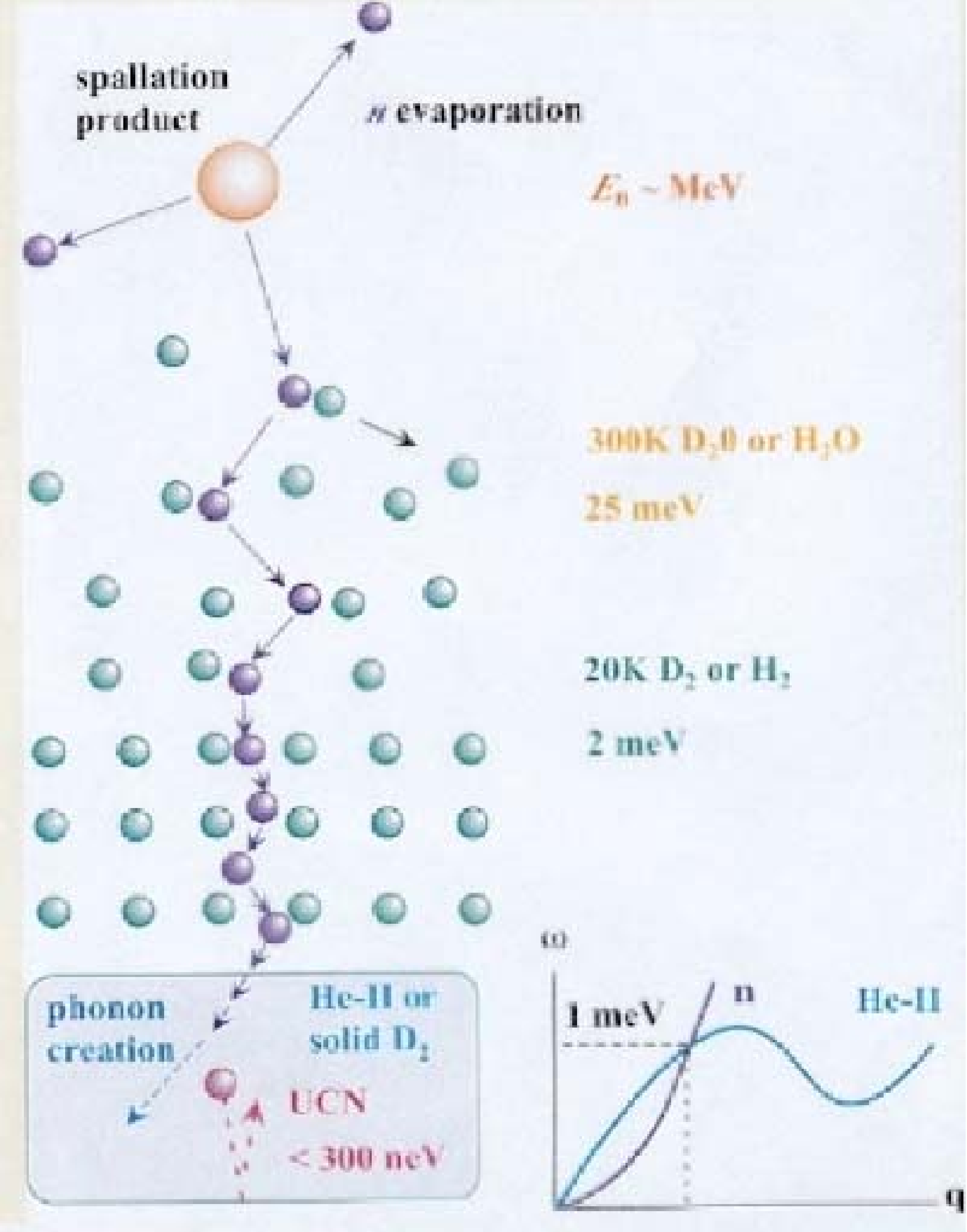
$$\tau_{n\bar{n}} > (\sqrt{\dot{N}_{ucn} \cdot 3 \cdot 10^{7}}) \cdot \sqrt{500 \cdot 1} \cdot 1 = 8.6 \cdot 10^{7} s \quad \Rightarrow \quad \dot{N}_{ucn} > 5 \times 10^{5} / s$$

$$\tau_{n\bar{n}} > (\sqrt{\dot{N}_{ucn} \cdot 3 \cdot 10^{7}}) \cdot \sqrt{500 \cdot 1} \cdot 1 = 1.0 \cdot 10^{9} s \quad \Rightarrow \quad \dot{N}_{ucn} > 6.6 \times 10^{7} / s$$

Technical Challenges with Experiments using UCN:

Need more UCN flux!

Neutron Cooling

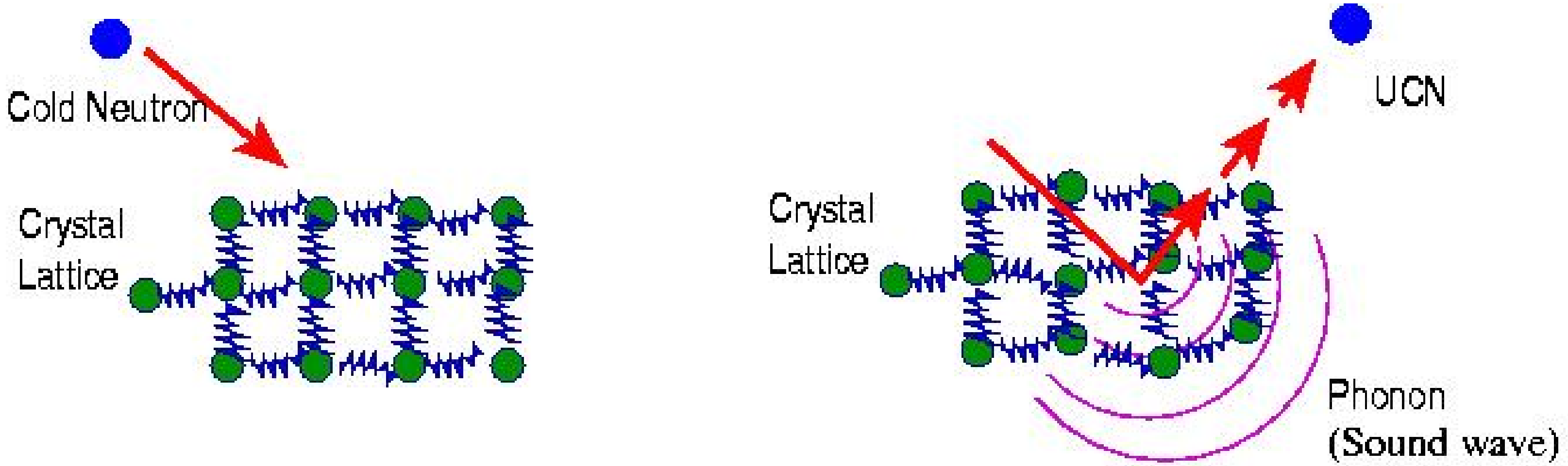


Masuda, Proceedings of the 3rd UCN workshop

Superthermal Process

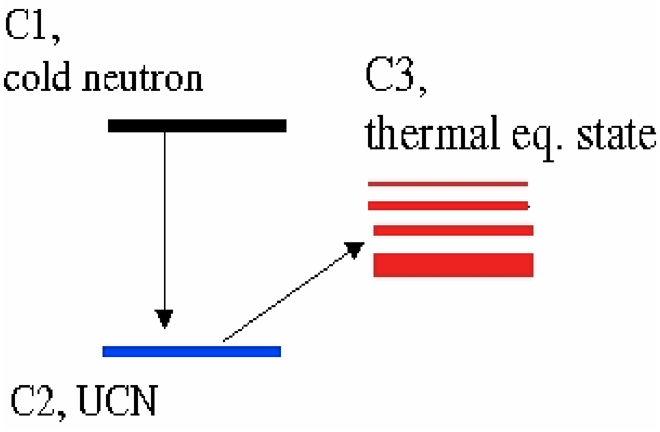
R. Golub and J. M. Pendlebury, Phys. Lett, A53, 133 (1975)

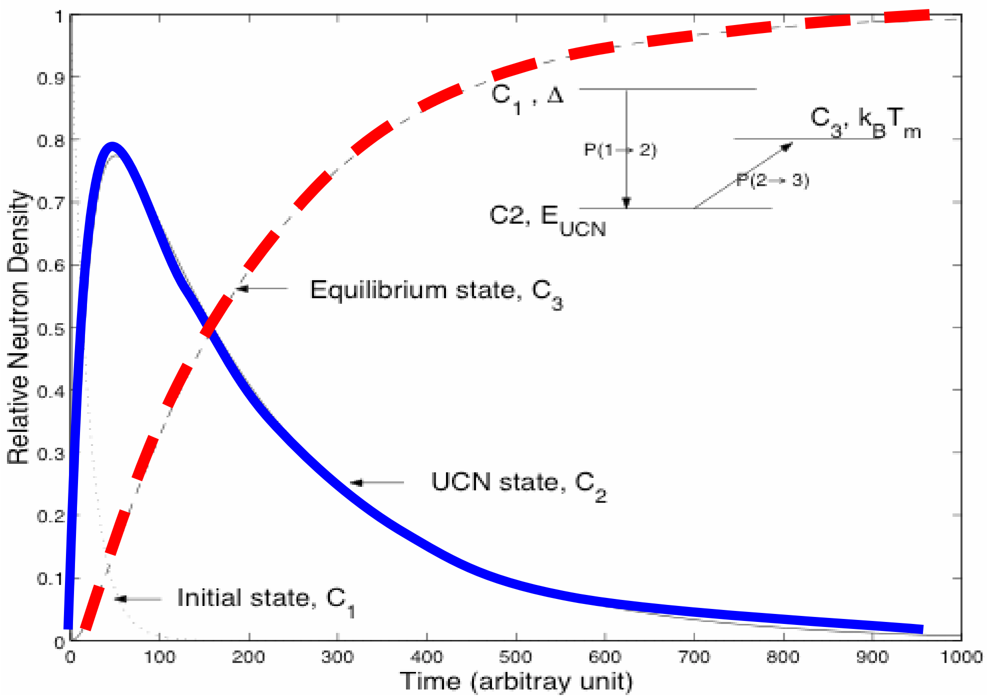
- Cold neutrons downscatter in the solid, giving up almost all their energy, becoming UCN.



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

Dynamics of UCN Production --
Defeat thermal equilibrium

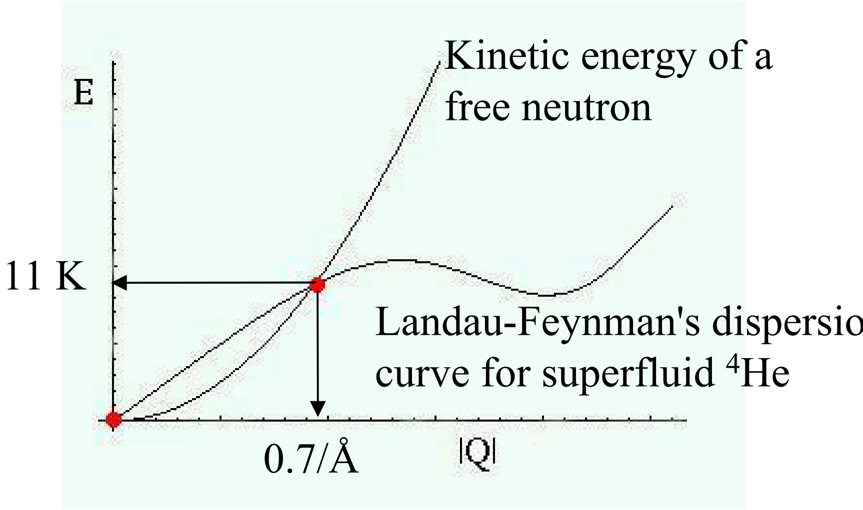




- Lifetime of UCN in the source material is a critical parameter in the establishment of large UCN densities.
- Extract UCN out of the source before it is thermalized ⇒ Spallation N source + Seperation of the source and the storage + a UCN Valve

Superfluid ^{4}He – UCN production

- Isotropic superfluid ^{4}He
  - – Energy excitation is isotropic.
  - □ Neutron scattering is isotropic.



- UCN can accumulate until the production rate = loss rate

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

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

Superthermal gain

Superfluid ^{4}He – UCN loss

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

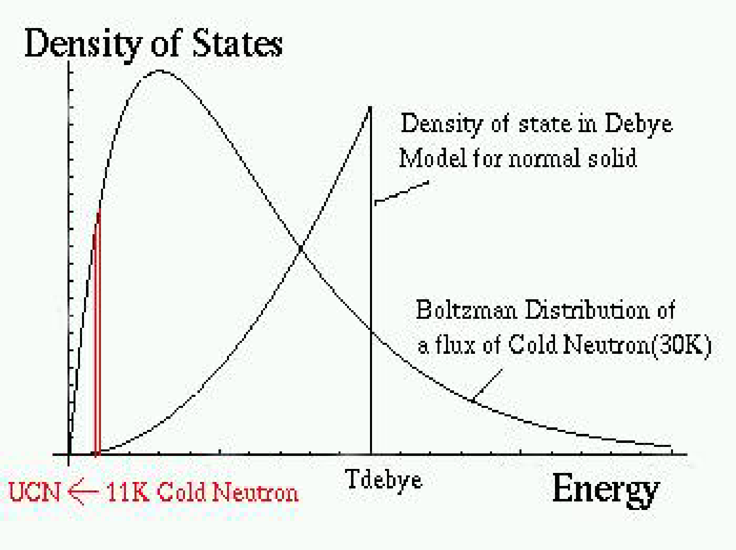
Isotop	σ_{coh}	σ_{inc}	σ_a	σ_s/σ_a	**purity**	**Debye T**
^{2}D	5.59	2.04	0.000519	1.47×10^4	99.82	110
^{4}He	1.13	0	0	∞		20
^{15}N	5.23	0.0005	0.000024	2.1×10^5	99.9999	80
^{16}O	4.23	0	0.00010	2.2×10^4	99.95	104
^{208}Pb	11.7	0	0.00049	2.38×10^4	99.93	105

Solid Deuterium –UCN production (I)

- Incoherent contribution (**σ_{inc} = 2.04 barn**)
  (due to the difference of singlet and triplet scattering)
  - No momentum delta function in the scattering cross section.

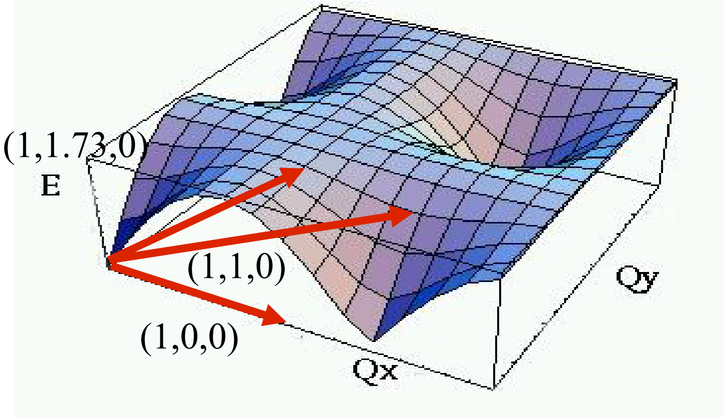
$$\sum_q \rightarrow \int d\omega Z(\omega)$$

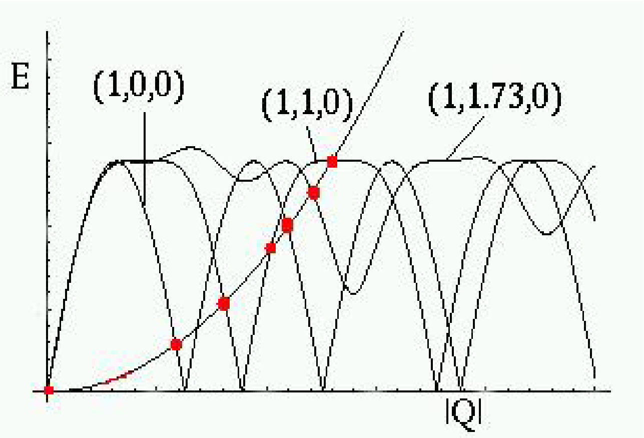
☐ All the Cold Neutron with energy smaller than the Debye T could become UCN through incoherent phonon creation.



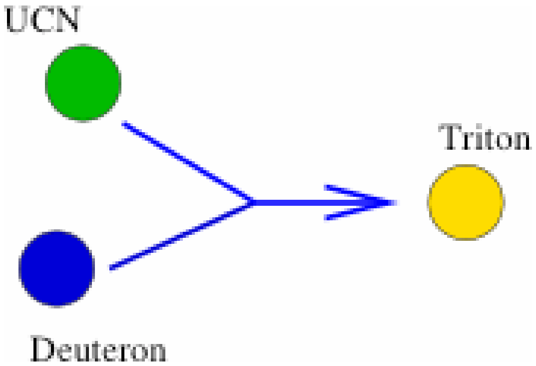
Solid D2 – UCN production (II)

- Coherent contribution (**σ_{coh}= 5.59 barn**)
  - Momentum and energy conservations are still strictly hold.
  - The anisotropic dispersion relation broadens the range of conditions for single phonon creation process.
  - In a cold neutron flux with a continuous spectrum, more neutrons could participate in the UCN production.



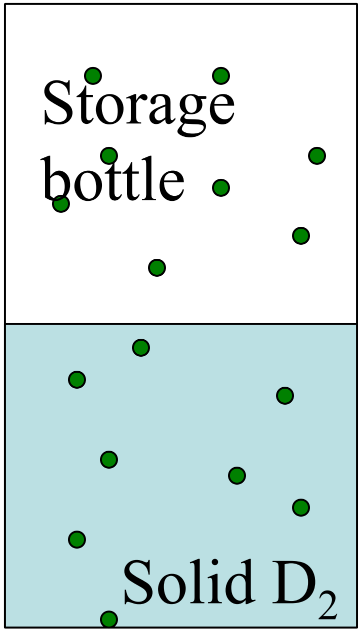


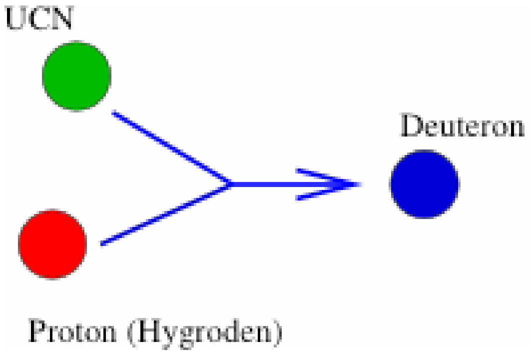
Solid Deuterium - UCN Loss



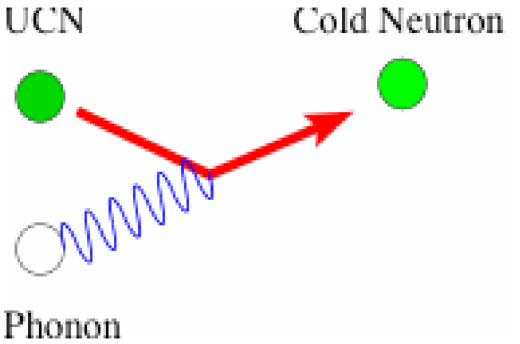
Nuclear absorption by S-D_2

$\tau \sim$ 150 msec



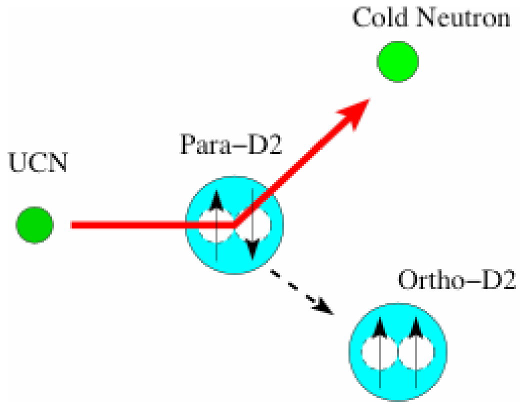


Nuclear absorption by Hydrogen Impurities, **$\tau \sim$ 150 msec/0.2% of H**



UCN upscattering by phonons

$\tau \sim$ 150 msec at T = 5K

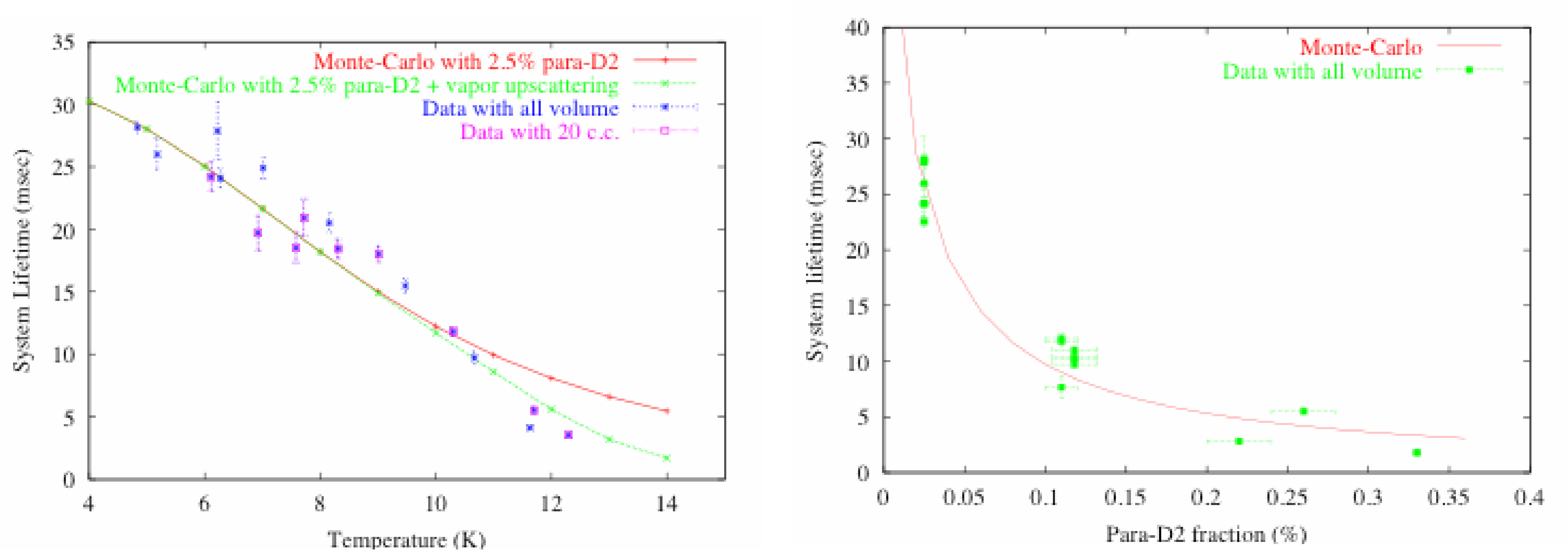


UCN upscattering by para-D_2

$\tau \sim$ 150 msec/1% of para-D_2

UCN lifetime in S-D$_2$

LANL UCN prototype source (2000)

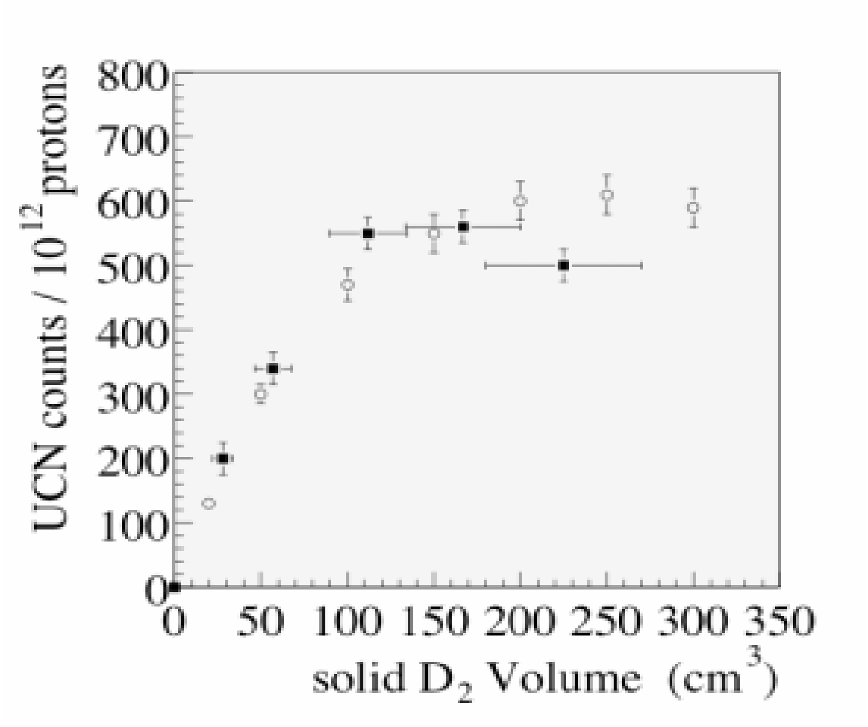


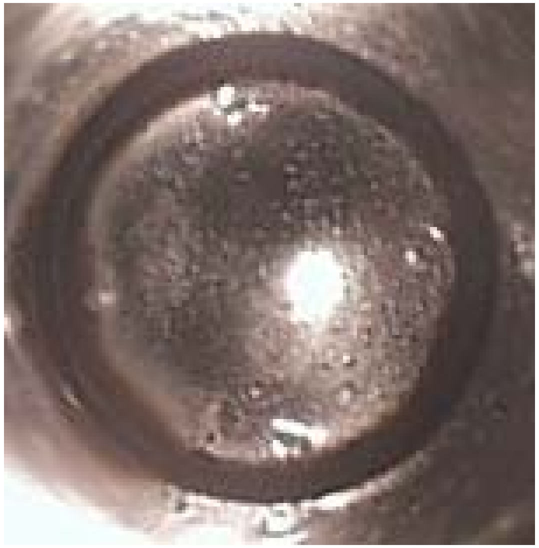
C. Morris *et al.*, Phy. Rev. Lett. **89**, 272501 (2002)

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

LANL UCN prototype source (2000)

Volume Scan



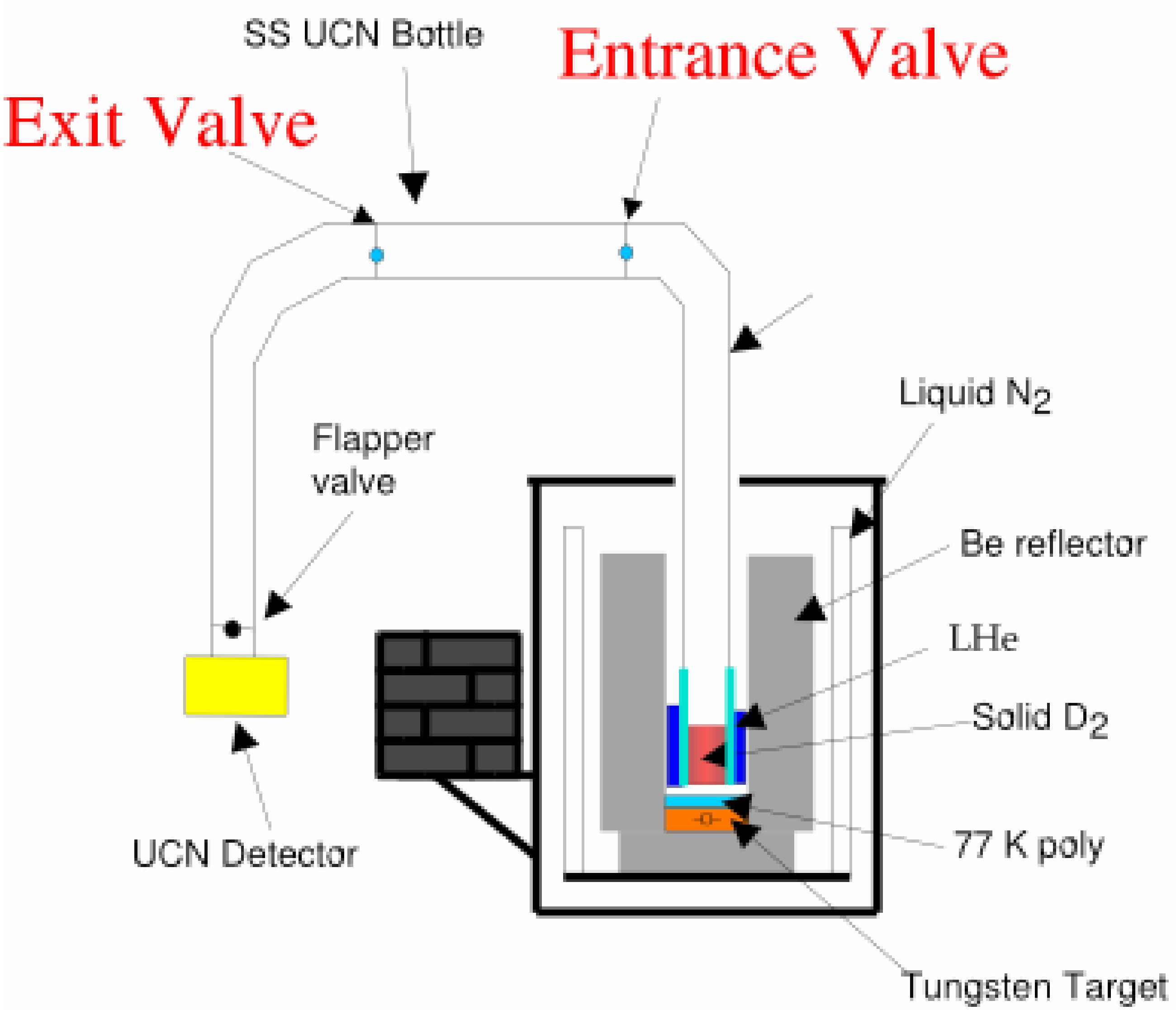


- UCN yield saturates above 200 c.c ⇒ mean free path = 8 cm

  Resulted from UCN incoherent elastic scattering (random walk).
- No additional scattering due to the finite crystal effects.

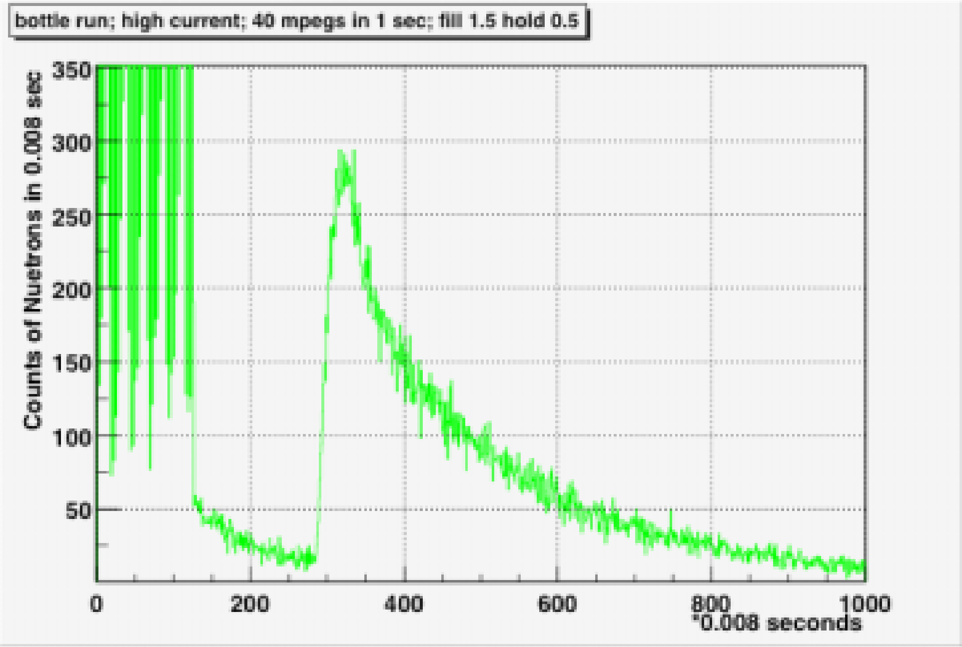
UCN Production Measurement --Bottle Technique

LANL UCN prototype source

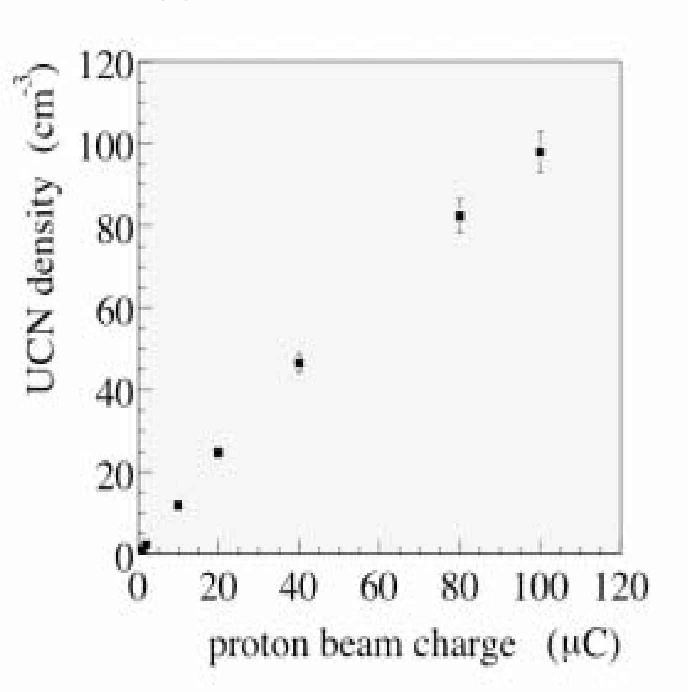


C. Morris *et al.*, Phy. Rev. Lett. 89, 272501 (2002)

Los Alamos s-D_2 UCN Prototype Source



WORLD RECORD



- Source has para-D_2: 4%
- Bottled UCN density: **100 UCN/c.c**. in a S.S. bottle 1 m away from the source. (world record)
- **UCN Flux = 3.8×10^4 UCN/s**
- Noticeable beam heating on solid deuterium.

Source Candidates

Isotope	σ_{coh}	σ_{inc}	σ_{abs}	$\sigma_{tot}/\sigma_{abs}$	purity	T_{Debye}
^{2}D	5.59	2.04	5.2e-4	**1.47e+4**	99.82	110
^{4}He	1.13	0	0	∞		20
^{15}N	5.23	5e-4	2.4e-5	**2.1e+5**	99.9999	80
^{16}O	4.23	0	1.0e-4	**2.2e+4**	99.95	104
^{208}Pb	11.7	0	4.9e-4	**2.4e+4**	99.93	105

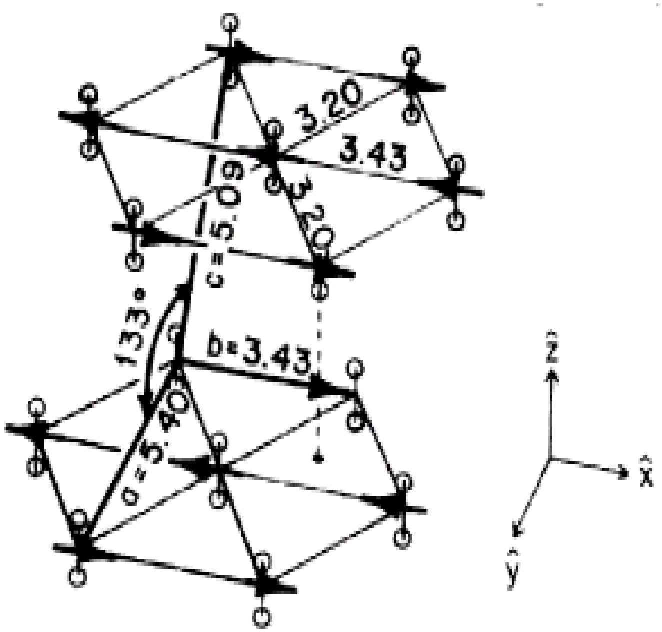
Too Heavy !

Too Expensive !

Solid Oxygen as a UCN Source

- Electronic spin S=1 in O_2 molecules
- Nuclear spin = 0 in ^{8}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.

⇒ A very large source possible.

Neutron Scattering in Solid O_2

- Spin(n) -Spin(e) coupling

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

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

(Spin)×(Translation)

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

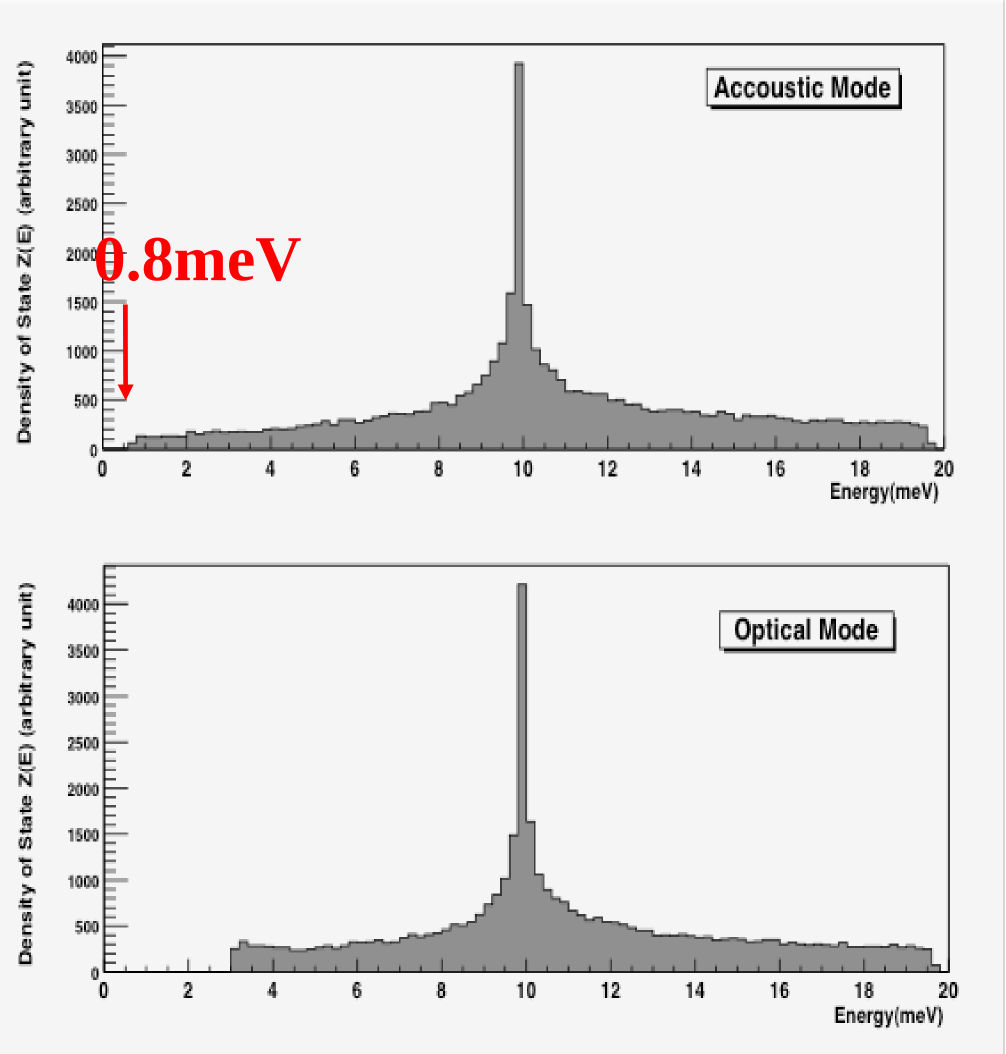
$$\Downarrow \qquad\qquad \Downarrow$$

(1+magnon)×(1+phonon)

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

Neutron-Magnon Scattering in S-O_2

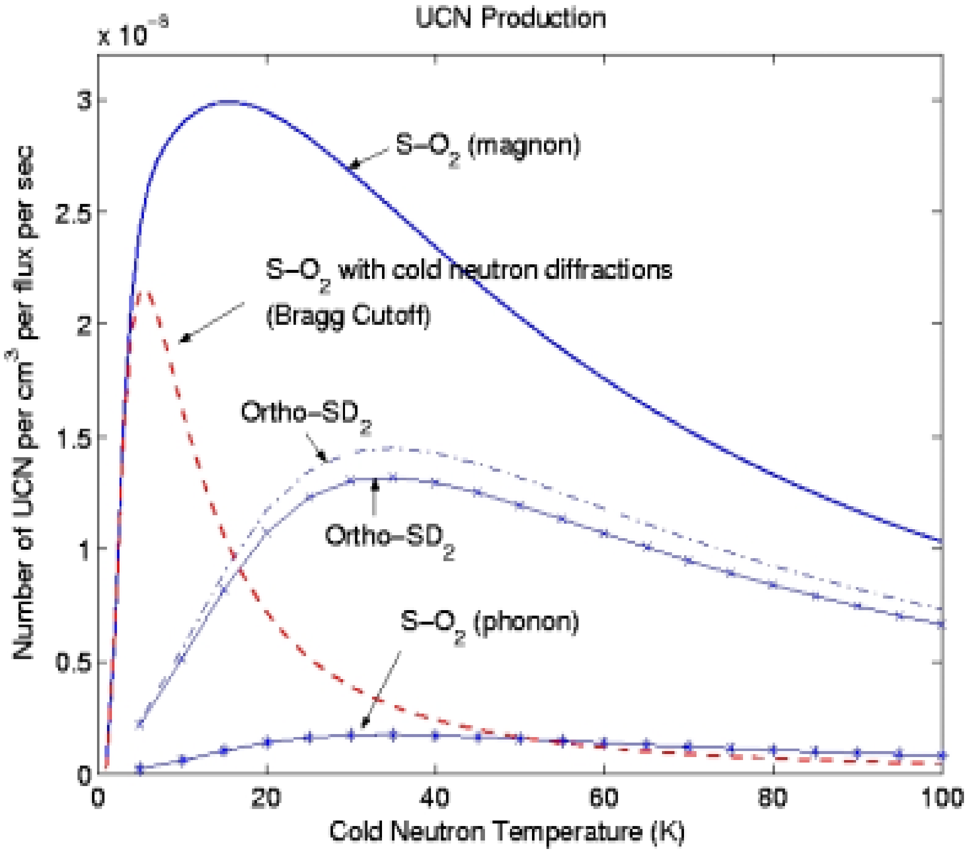
Density of States (Magnon)



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

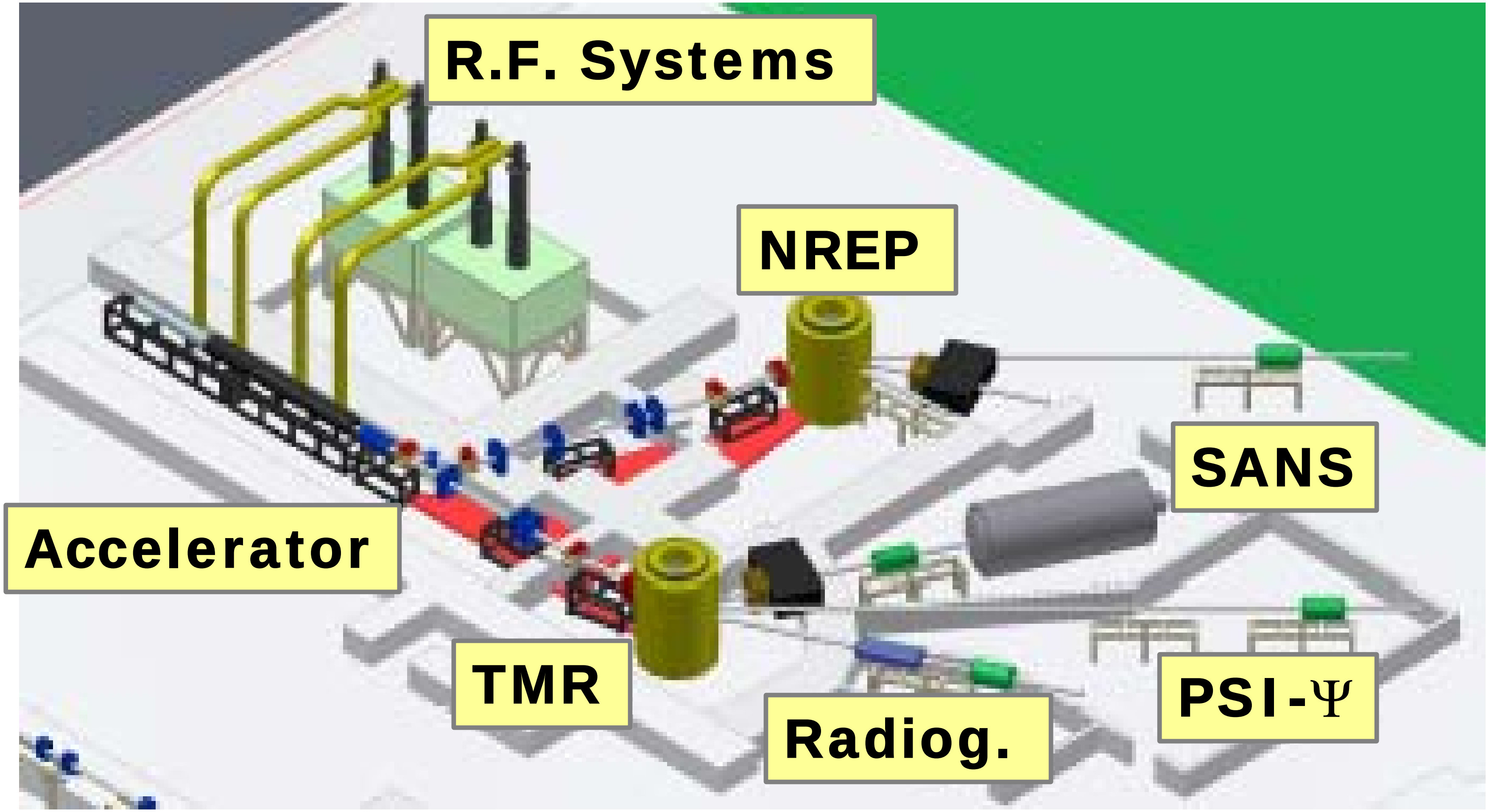
UCN production in Solid Oxygen

- Production rate
  - P = 2.7 × 10^{-8} Φ_0 (30K CN in S-O2
  - P = 3.0 × 10^{-8} Φ_0 (15K CN in S-O2
  - P = 1.5 × 10^{-8} Φ_0 (30K CN in S-D2
  - **Gain ~ 2 relative to S-D_2**
- Lifetime
  - 375 ms in S-O_2
  - 40 ms in S-D_2
  - **Gain ~ 10**
- Volume gain, $(l)^n$, n= 1-3
  - l_{ucn} = 380 cm in S-O_2
  - l_{ucn} = 8 cm in S-D_2
  - **Gain ~ 50 - 10^5**



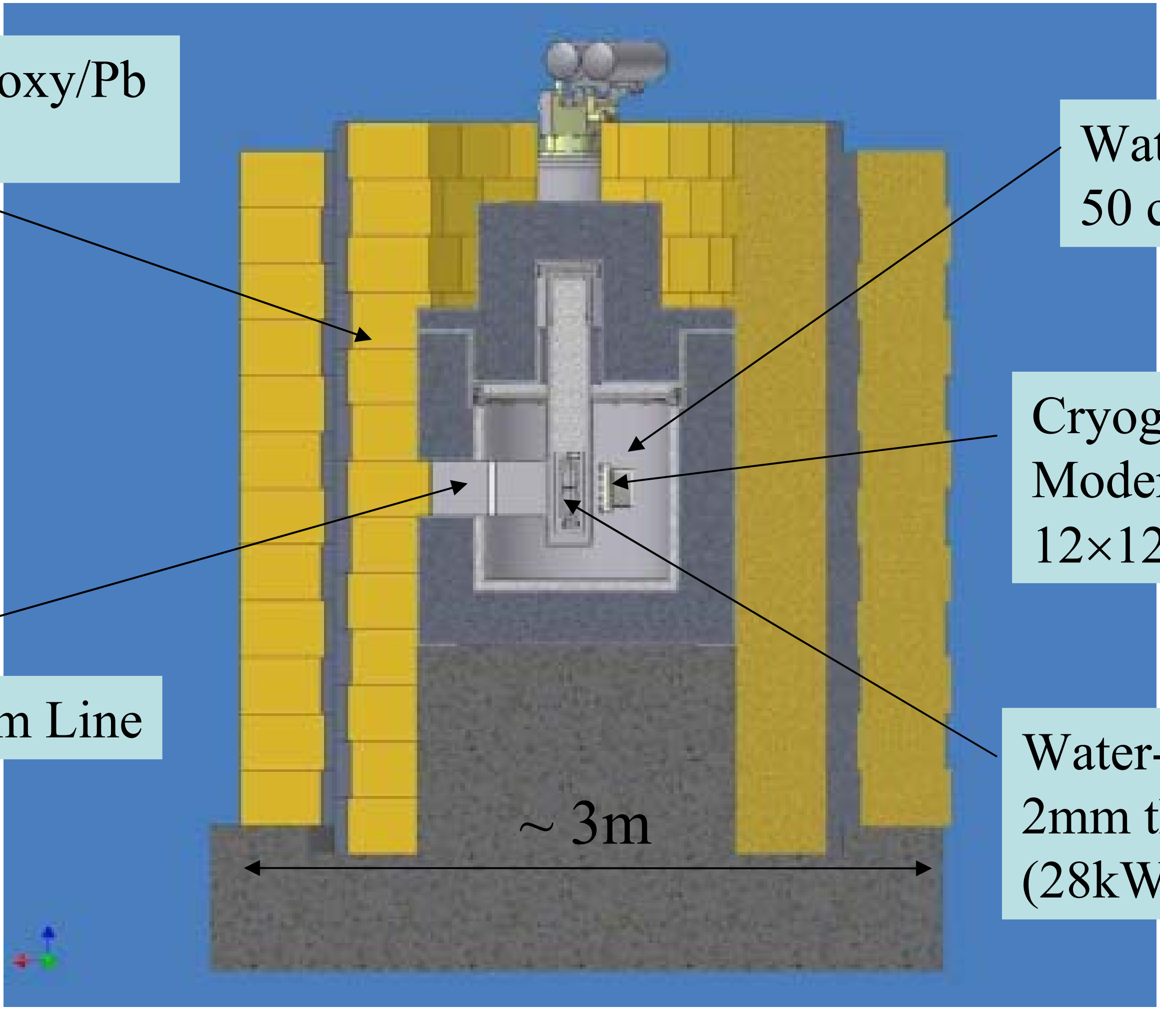
Compared with S-D_2,
Gain > 1000 is possible !

Low Energy Neutron Source (LENS) at IUCF (floor plan-2007)



Target Moderator Reflector (TMR)

LENS, IUCF



Borex/PE/Expoxy/Pb complex

Water Reflector
50 cm dia.

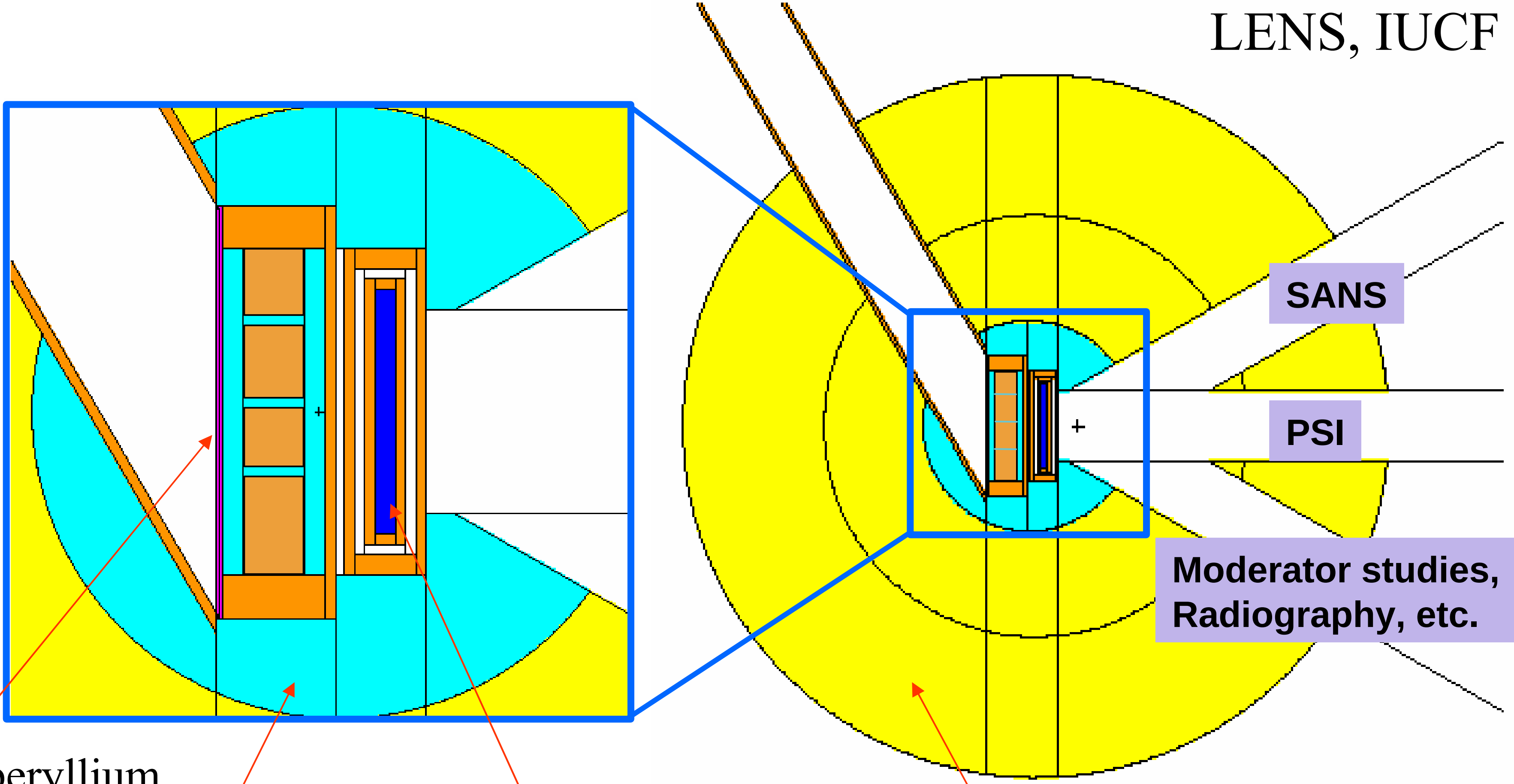
Cryogenic (Methane)
Moderator (22K)
$12\times12\times1\ \mathrm{cm}^3$

Neutron Beam Line

Water-cooled Be Target
2mm thick
(28kW cooling power)

Target/Moderator/Reflector (TMR) Assembly

LENS, IUCF



Thin beryllium
production target

Methane moderator

inner reflector – water

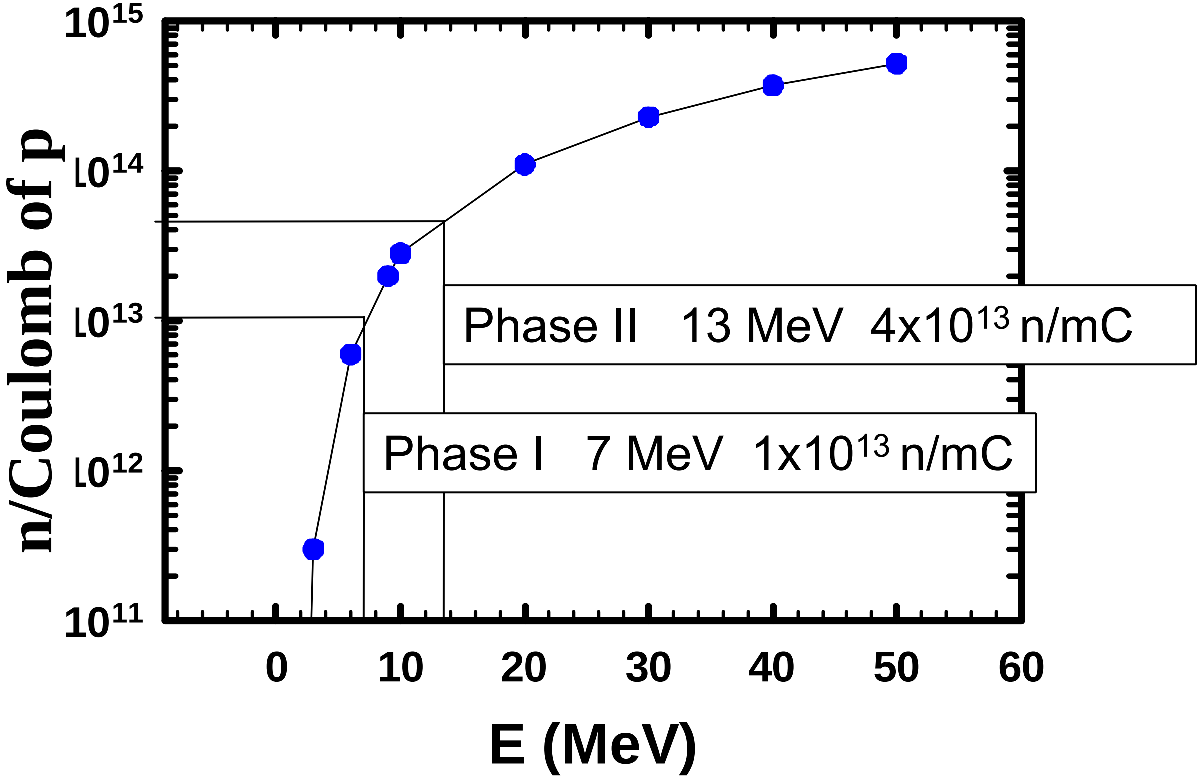
Outer shielding – lead
and poly layers

Neutron Production at LENS

Neutron Source:

based on low-energy (p,n) and (p,pn) reactions (E_p<14MeV) in Be.

Yield ~ 0.01 n/p @13 MeV
~ 0.002 n/p @ 7MeV



p+Be Neutron Production

Phase II 13 MeV $4x10^{13}$ n/mC

Phase I 7 MeV $1x10^{13}$ n/mC

Time line:

- Phase I (Early 2005: 7MeV 10mA, 1% DF; **10^{12} n/s**).

- Phase II (Fall 2006: 7Mev, 50mA, 5% DF; **$2x10^{13}$ n/s**)

– Eventual power (13MeV, 50mA, 5% DF; **10^{14} n/s**)

LENS produces its first “cold” neutron beam

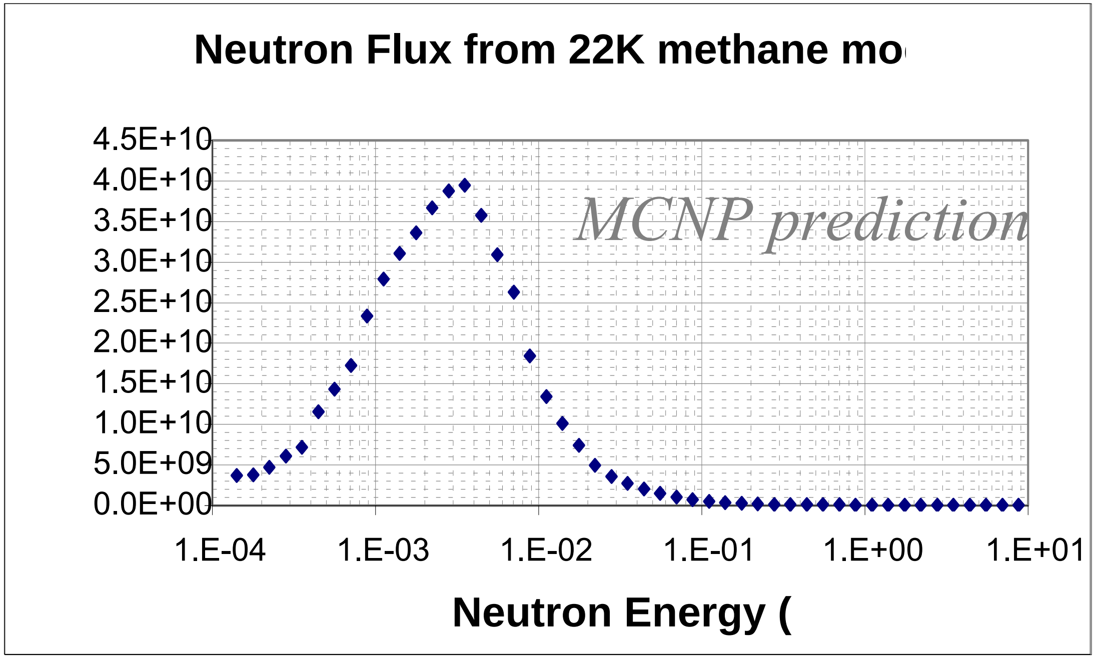
Mark Leuschner, et. al.
April 26, 2005

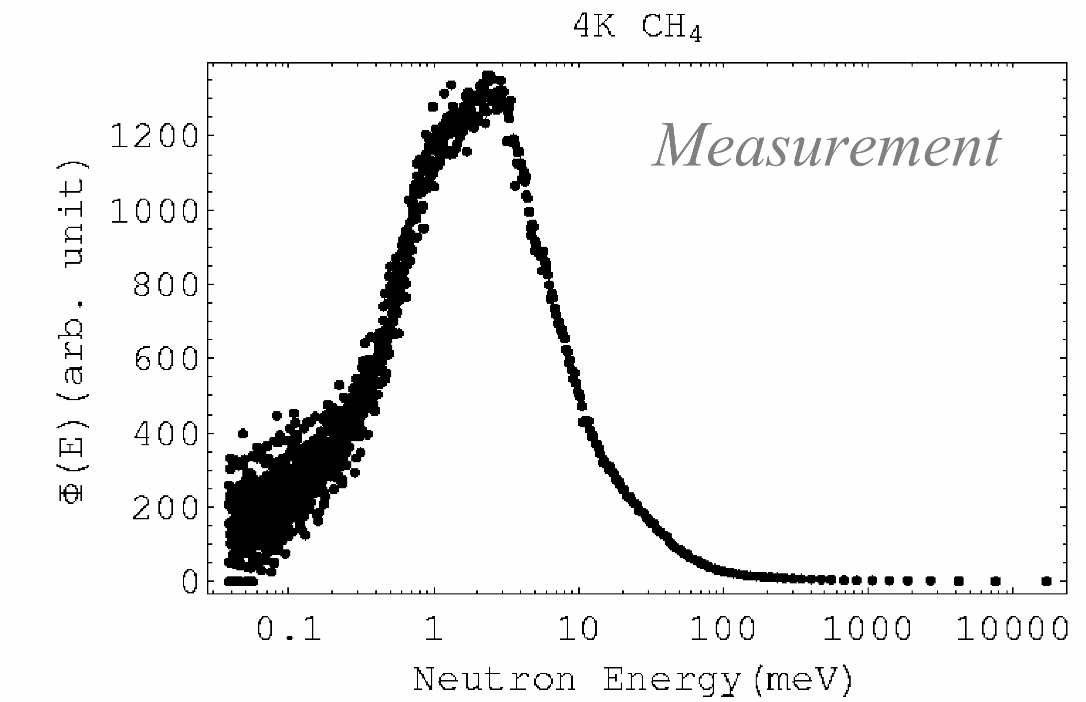
- methane moderator (1 cm thick, 3.6 K.)

- two component spectrum
  (25 K, 157 K.)

- The moderator is very thin, so the neutrons that pass through it do not quite reach thermal equilibrium.

- Spin temperature is too high.
  (YunChang Shin)



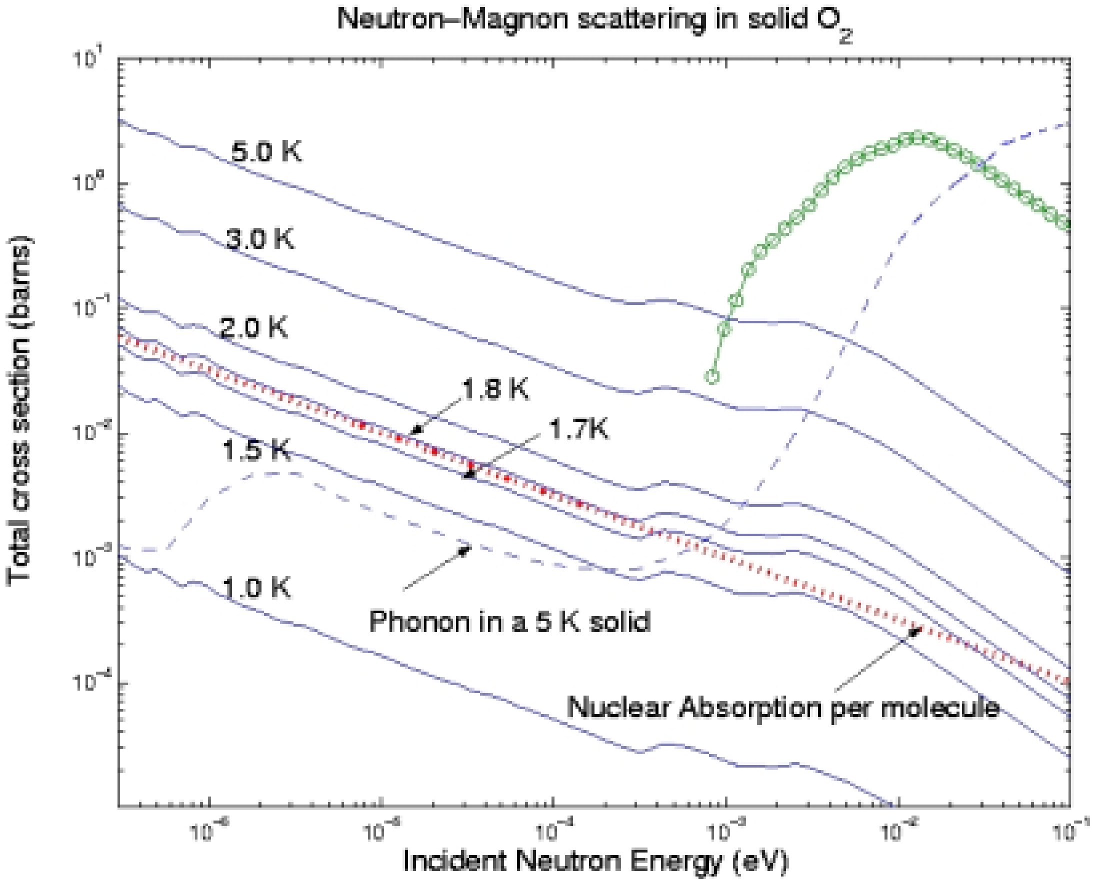


UCN source at LENS

- Features
  - (p,n) reactions make **fewer fast neutrons and gammas** in source ⇒ might be able to run CW. (Has the benefit of a reactor source)
  - LENS will have a **variable pulse width** (from <5 μs to 1.0 ms or more).
  - In long-pulse mode, LENS will have a **time-averaged cold neutron intensity comparable to an existing national user facility (IPNS).**
- **Cold moderators (4~22K)**
  - **Rad damage from source is low for LENS**
  - Kr-doped CH4 (free rotor), 2-methyl-pyridine (CH3 free rotor),
- **UCN flux estimate (in S-O_2)**
  - Cold neutron flux: **2×10^{10} CN/cm^2-s** (Patrick McChesney)

    (proton: 13 MeV, 2.5mA(avg), with 4K poly moderator, T_{CN}=35K)
  - UCN density: **300 UCN/cc**, UCN fluence: > **3 $\times10^5$ UCN/s (with 500 cc S-O_2)**
  - Heat load ~ 1 W

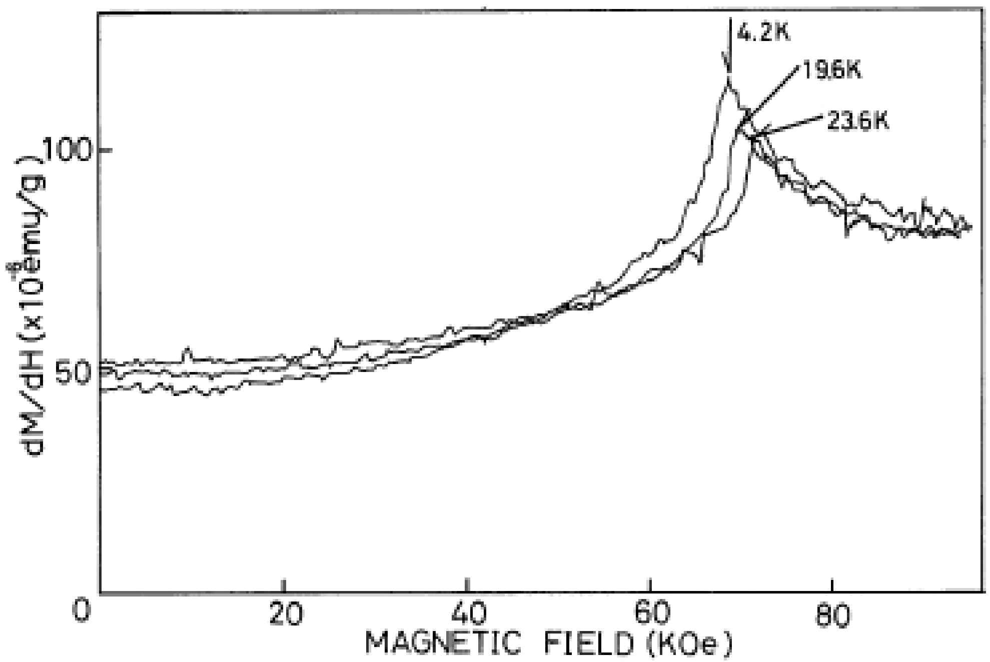
Challenges



- **1.8 K cryogenic.**
  - Larger gamma heating and smaller thermal conductivity than S-D_2 ⇒ challenges on cryogenic engineering
  - Requires a fast thermal break (50K to 2K) over a few cm.

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

Probe the Magnon Mechanism using a B field



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

- An external magnetic field to perturb the magnon dispersion curve
  - Change the density of states.
  - Optimize UCN production.
- Spin flop transition around 7 Tesla ⇒ AF magnons turned off.
- **Definitive demonstration of the magnon mechanism.**

Experiments of UCN Production from S-O_2

- PSI, Switzerland
- **FunSpin** beamline in SINQ

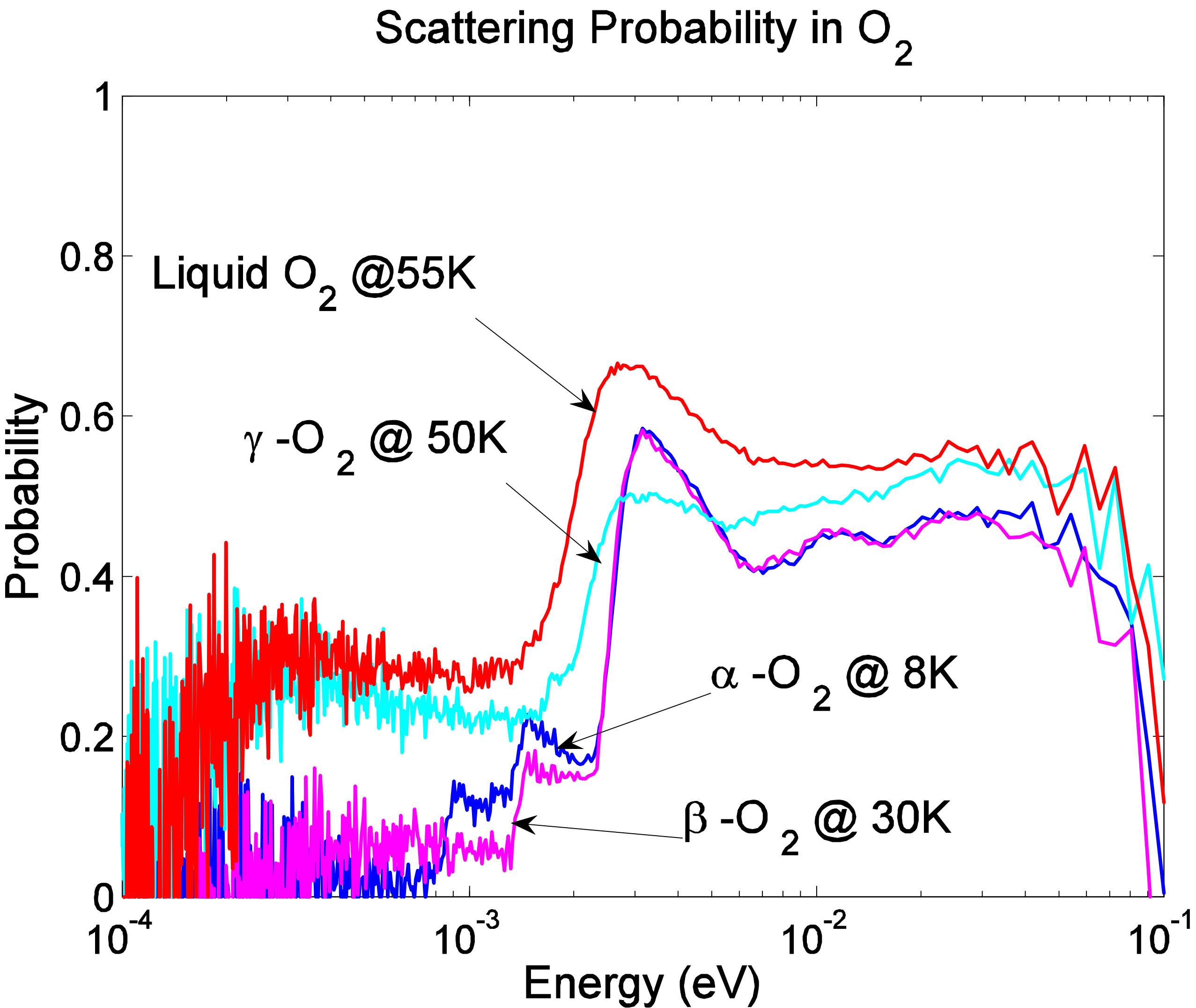
  $\Phi_{CN} = (4.5 \pm 1.0) \times 10^7/\mathrm{cm}^2\text{-s-mA}$

  - with 1.2mA on SINQ target
  - PSI UCN group has demonstrated UCN production in s-D_2.
  - UCN count rate in the detector of 0.4/s, with a S/N ratio of 40 to 1.

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

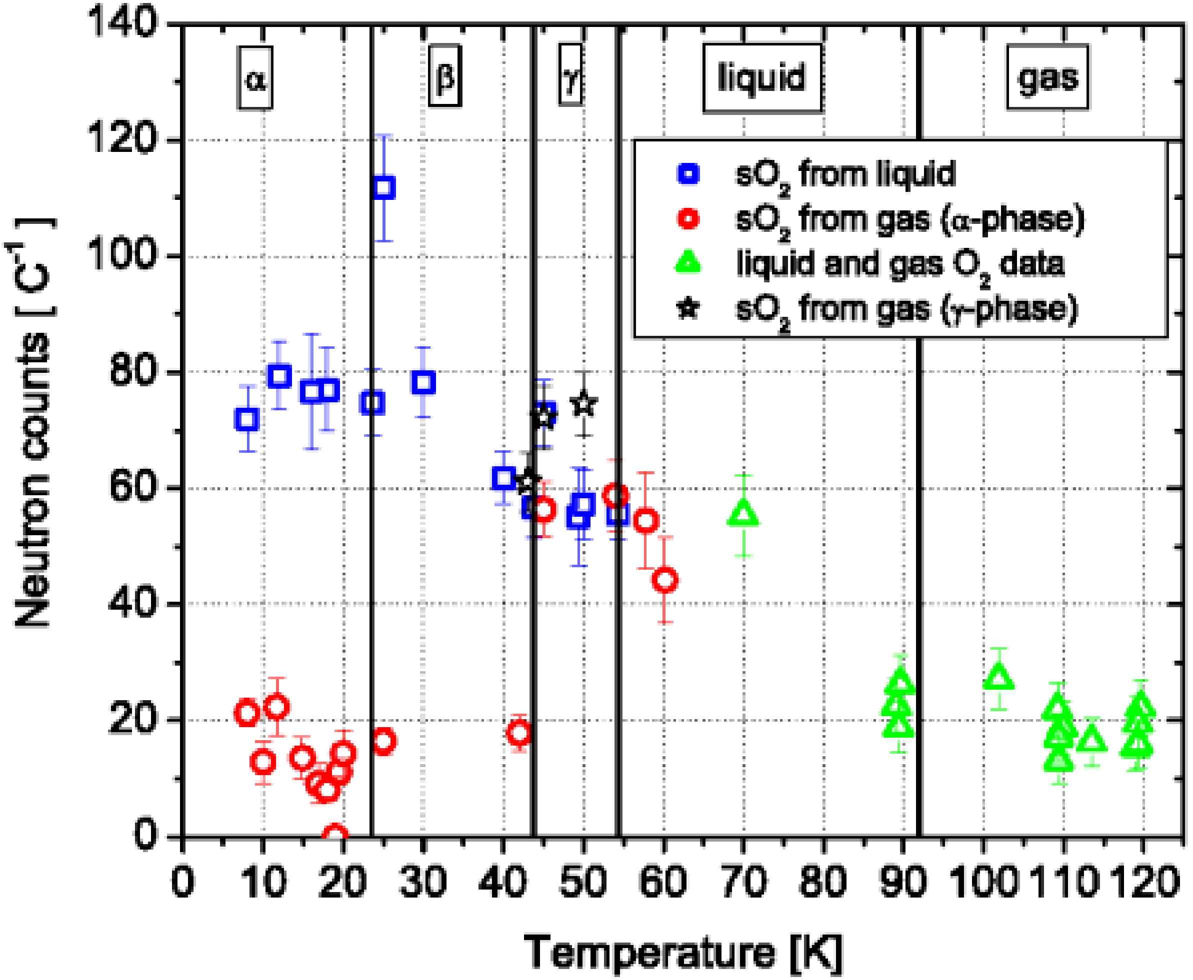
- Similar count rate is expected using solid oxygen
  - assuming the UCN extraction is not hindered by the very different physical properties of oxygen solid (compared with s-D_2).

Cold Neutron Transmission (TOF)



- Flight path =2.83m.
- Neutron Chopper.
- Scattering probability
  - $I_0(E)-I(E)/I_0(E)$
- Features:
  - Bragg edges
  - Additional Bragg peak in alpha phase. (indicate the presence of a magnetic structure.)

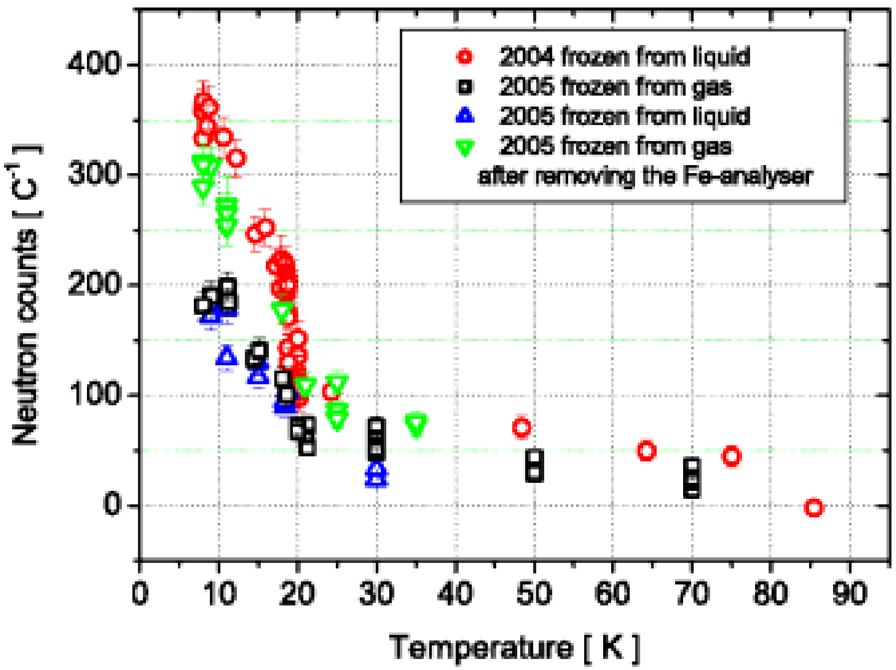
UCN Production in Solid O_2

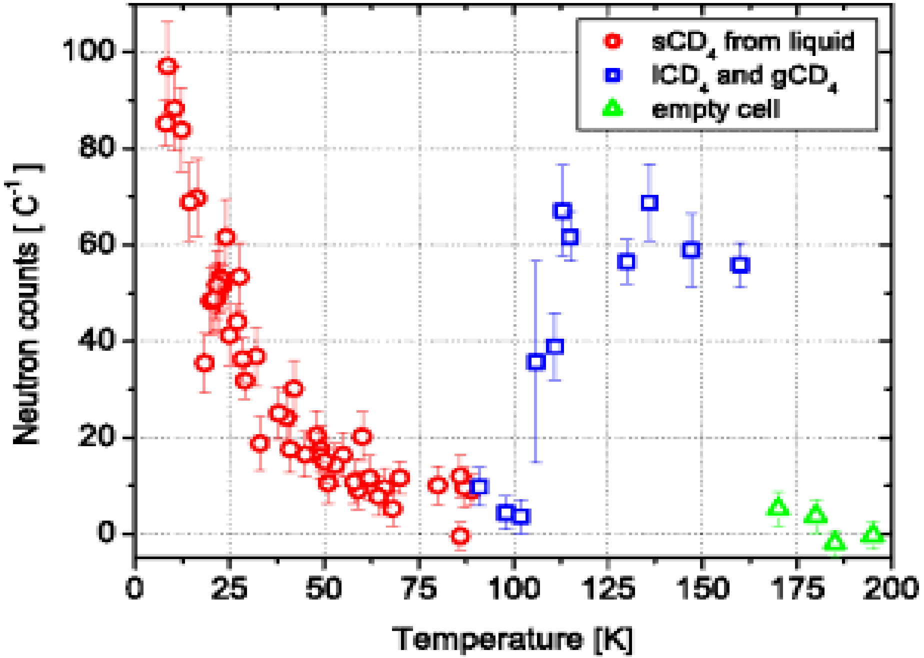


- No superthermal temperature dependence.
  - Indicates unknown source of UCN loss.
- UCN yield is correlated with how the crystal is prepared.
- The UCN yield (best number) is ~ 3 times less than s-D_2.
- A peak in the α-β phase transition. (critical scattering?)

UCN Production in D_2 and CD_4

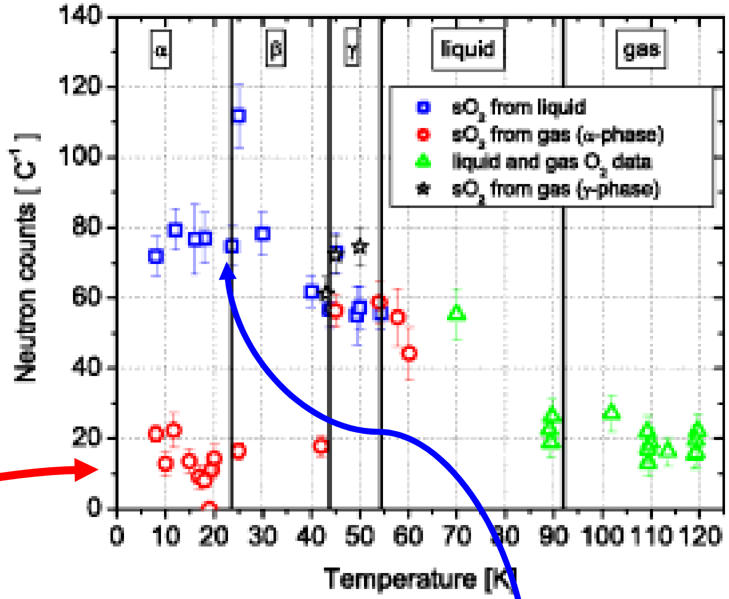
- From D_2 and CD_4.
- Signature temperature dependence of a superthermal source.



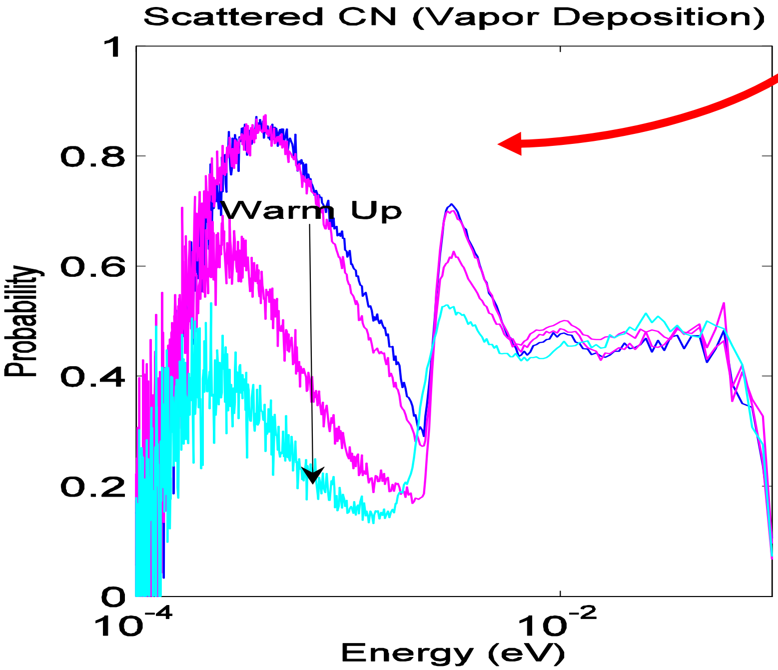


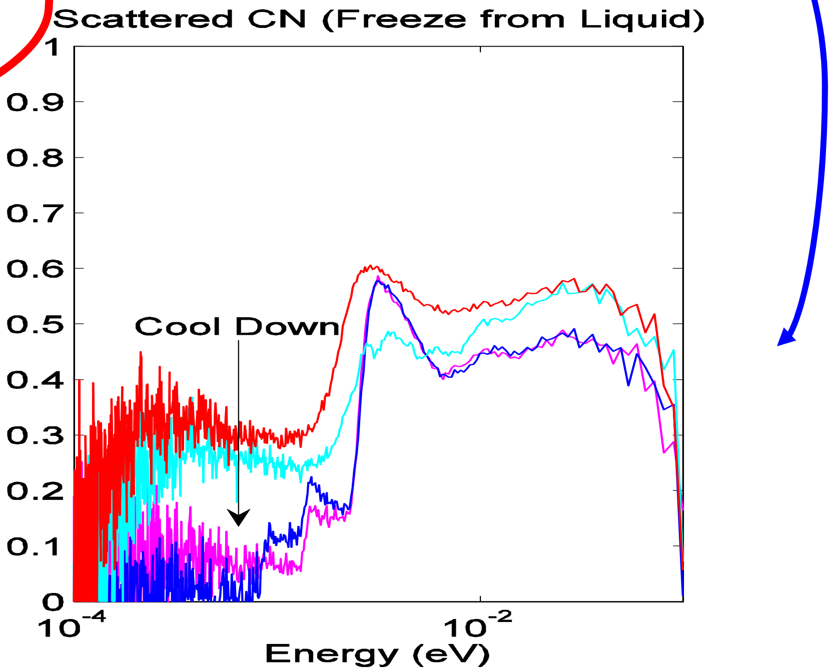
UCN Production vs. CN Transmission

- Net UCN yield is strongly correlated with CN transmission data.



Material: solid O_2





Conclusions

- **Magnons in the AF phase of S-O_2 offer an additional channel for inelastic neutron scattering.**
  - UCN production rate in S-O_2~ (1-2) × in S-D_2.
  - UCN lifetime in S-O_2 ~ 10 × in S-D_2.
  - Larger source possible. (at least 10 × S-D_2)
  - UCN current output from S-O_2 (at least) 100 × from S-D_2

- **UCN Program at IUCF**
  - **LENS** provides a unique opportunity to study and develop a S-O_2 based UCN source.
  - Currently, we are setting up to study crystal growth. (YunChang Shin, John Ullman)
  - Planning to study magnetic field influence on the crystal preparation, energy dispersion curves, etc..

- **Broader impacts**
  - **A high UCN flux will make a UCN nnbar experiment possible.**