Cold Neutron and Ultracold Neutron Sources

Chen-Yu Liu
CL21@indiana.edu
Indiana University

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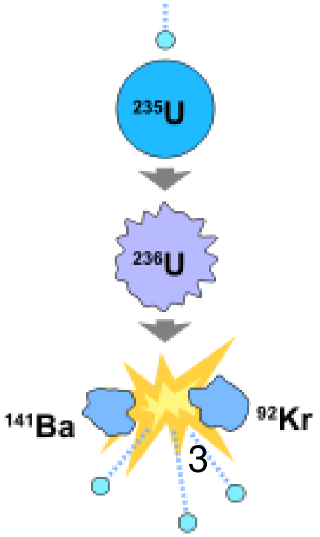
Outline

- Neutron Sources
- Cold Neutron Source
  - Neutron Moderation
  - Liquid Hydrogen, Ortho/para H_2
- Ultra-cold Neutron (UCN)
  - How are UCN useful?
    - Fundamental Neutron physics with UCN
  - How to make a lot of them?
    - Thermal, Turbine, Superthermal,…
- References:
  - "Ultracold Neutrons", Golub, Richardson, Lamoreaux
  - "Neutrons, Nuclei and Matter", J. Byrne

How to make free neutrons?

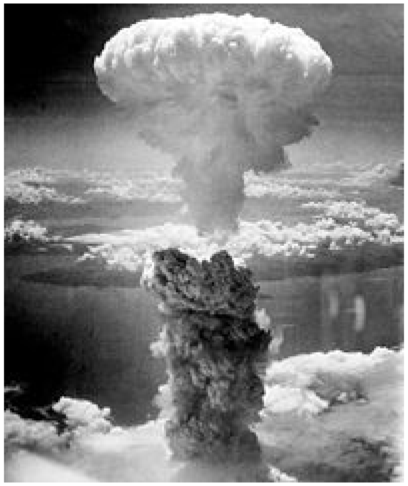
- Natural
  - Secondary particles generated by high-energy collisions between protons and nuclei at the top of the atmosphere.
    - Attenuated by the reaction $^{14}N(n,p)^{14}C$
  - $^{238}_{92}U$: spontaneous fission
- Artificial
  - (α,n) sources: $^{226}Ra+Be$, $^{239}Pu+Be$, $^{241}Am+Be$, ..
  - Photoneutron process: $^{2}H(\gamma,n)^{1}H$, $^{9}Be(\gamma,n)^{8}Be$
  - Accelerator sources
    - Bremsstrahlung from e^- accelerators for (γ,n) process
    - $^{2}H(d,n)^{3}He$, $^{3}H(d,n)^{4}He$, …
    - $^{3}H(p,n)^{3}He$, $^{7}Li(p,n)^{7}Be$, …
    - spallation
  - Fission chain reaction



CW vs Pulsed Source

- Continuous Wave (CW) Sources
  - Thermal fission reactors
  - Steady State Accelerator (SINQ)
  - Stable operation

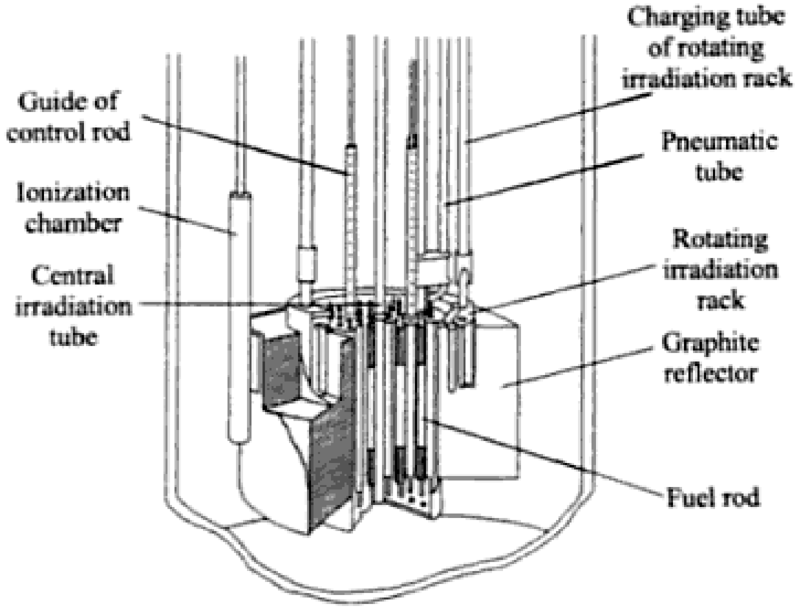
- Pulsed Sources
  - Intense Instantaneous Flux
  - Atomic bomb: single shot
  - Pulsed reactors
    - TRIGA reactor
  - Accelerator driven
    - Spallation source



TRIGA Reactor (Training, Research, Industry, General Atomic)

The TRIGA was developed to be a reactor that was designed to be "safe even in the hands of a young graduate student.“

– Frederic de Hoffmann, head of General Atomics



A quick removal of the control rod results in a short spike of the neutron flux of 100ms duration with an integrated neutron fluence of 10^{14} n/cm^2

Fuel: Zirconium (91%)+U(8%, 20% ^{235}U)+H(1%mass=50 atom%)

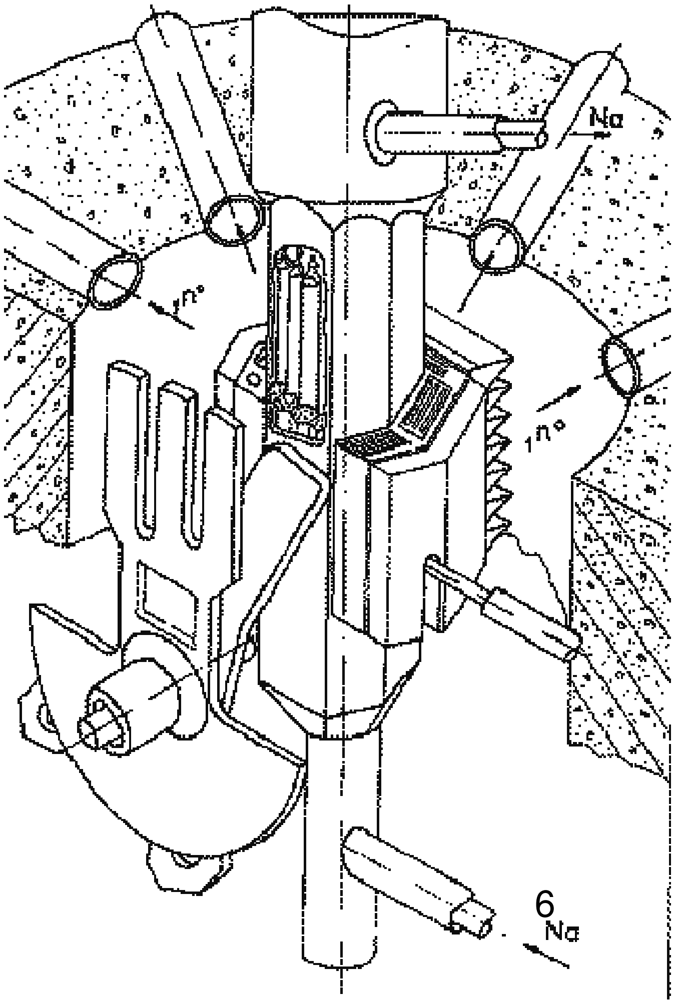
- Due to the H content, the fuel elements contribute directly to the moderation of neutrons.
- In order to induce a neutron burst, one control rod is removed rapidly from the reactor core. The reactor is made prompt critical with its power rises to 250MW within milliseconds.
- The fuel elements heat up to temperature of about 300 °C and the energy spectrum of the neutrons is shifted into the region of absorption resonances of ^{238}U. Thus, the reactivity of the reactor drops drastically.

Handbook of Nuclear Chemistry By A. Vértes, S. Nagy, Z. Klencsár

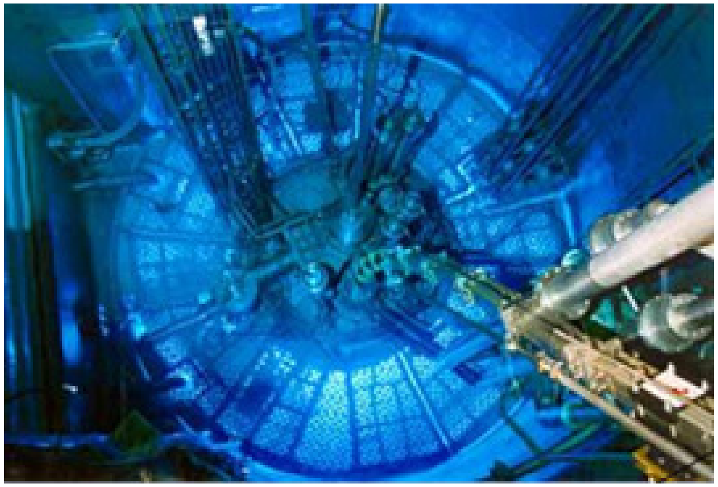
Fast Pulse Reactor (IBR-2, JINR, Dubna)

Power pulses with a frequency of 5 Hz are generated by reactivity modulators which are the <u>main moveable reflector (MMR)</u> and the <u>auxiliary moveable reflector (AMR)</u>. When they both approach the core, a power pulse develops.

Average thermal power	2 MW
Peak power in pulse	1500 MW
Power released between pulses	0.12 MW
Pulse repetition rate	5 Hz
Half-width of thermal neutron pulse	320 ms
Thermal neutron flux density from surface of the grooved-type moderators, space averaged: - time-averaged - at maximum of the pulse	 F~8x10^{12} n/(cm^{2}sec) F$_{max}$~5x10^{15} n/(cm^{2}sec) (effective for a beam)
Thermal neutron flux density in moderator at maximum of the pulse	2.4x10^{16} n/(cm^{2}sec)



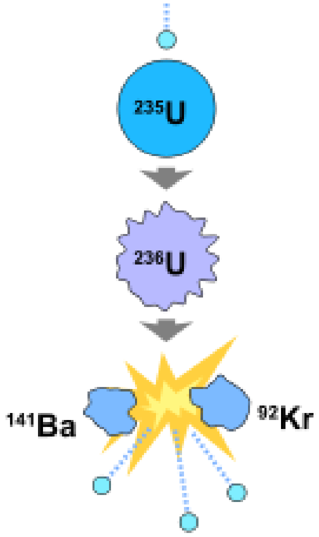
High Flux Reactors



- ILL, FRM-II
- Designed to produce a maximum neutron flux
  - Concentrate a maximum of fission events in a minimum of space.
  - Problem: remove the heat due to the fission reactions from such a small volume.
  - Use a single fuel element (for high mechanical stability) which resembles a turbine of a small core.
  - A total amount of 2010 m^3 of D_2O is pumped through the turbine-like fuel element, with an inner speed of 15 m/s.
  - 1000 times the flux of the TRIGA reactor.

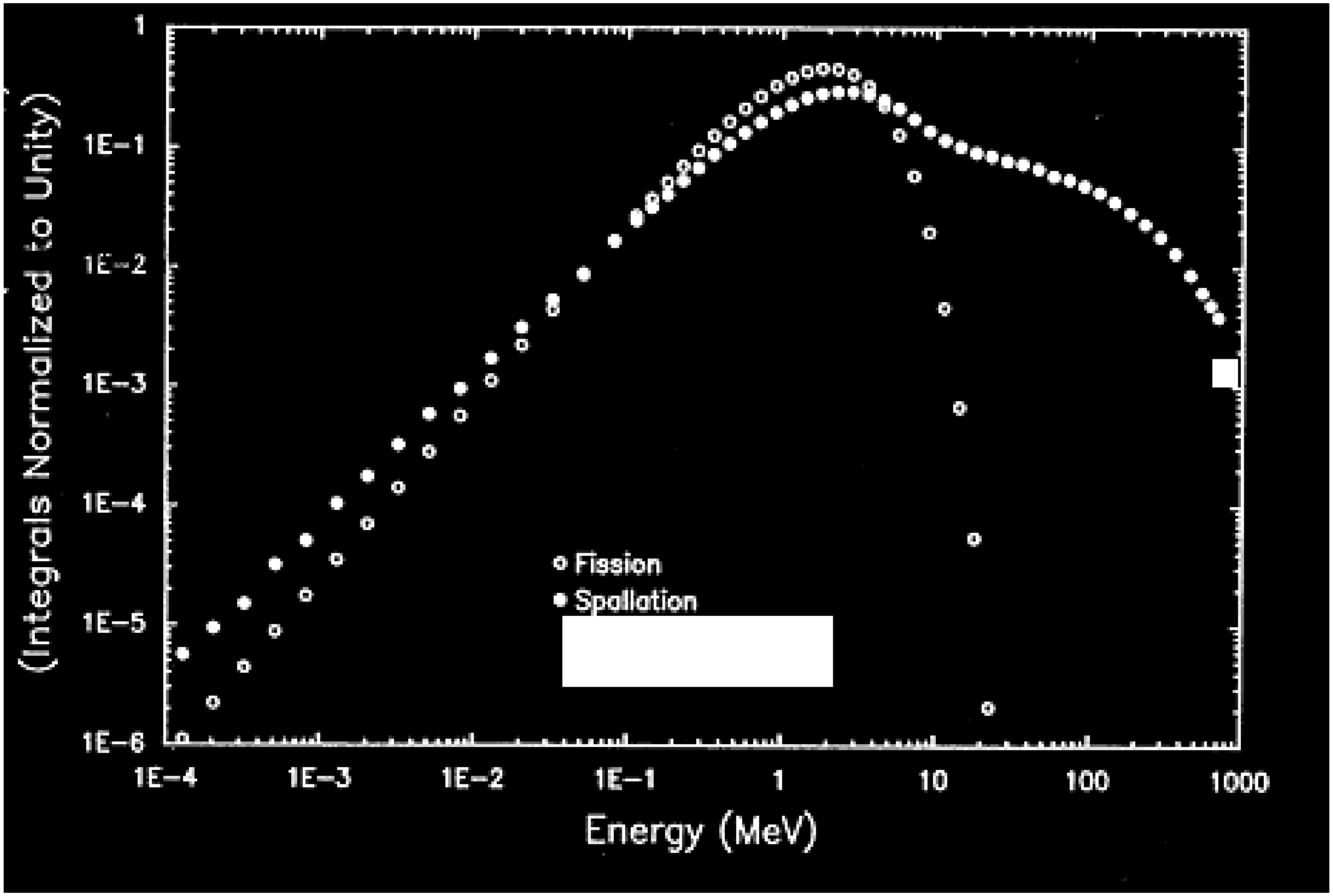
Research Reactors

Facility	Power (MW)	Neutron Flux (n/cm^2-s)
NIST	20	4×10^{14}
ILL	54	10^{15}
FRM-II	20	8×10^{14}
PNPI (WWR-M)	10	1.2×10^{14}
Pulstar	1	1.1×10^{13}



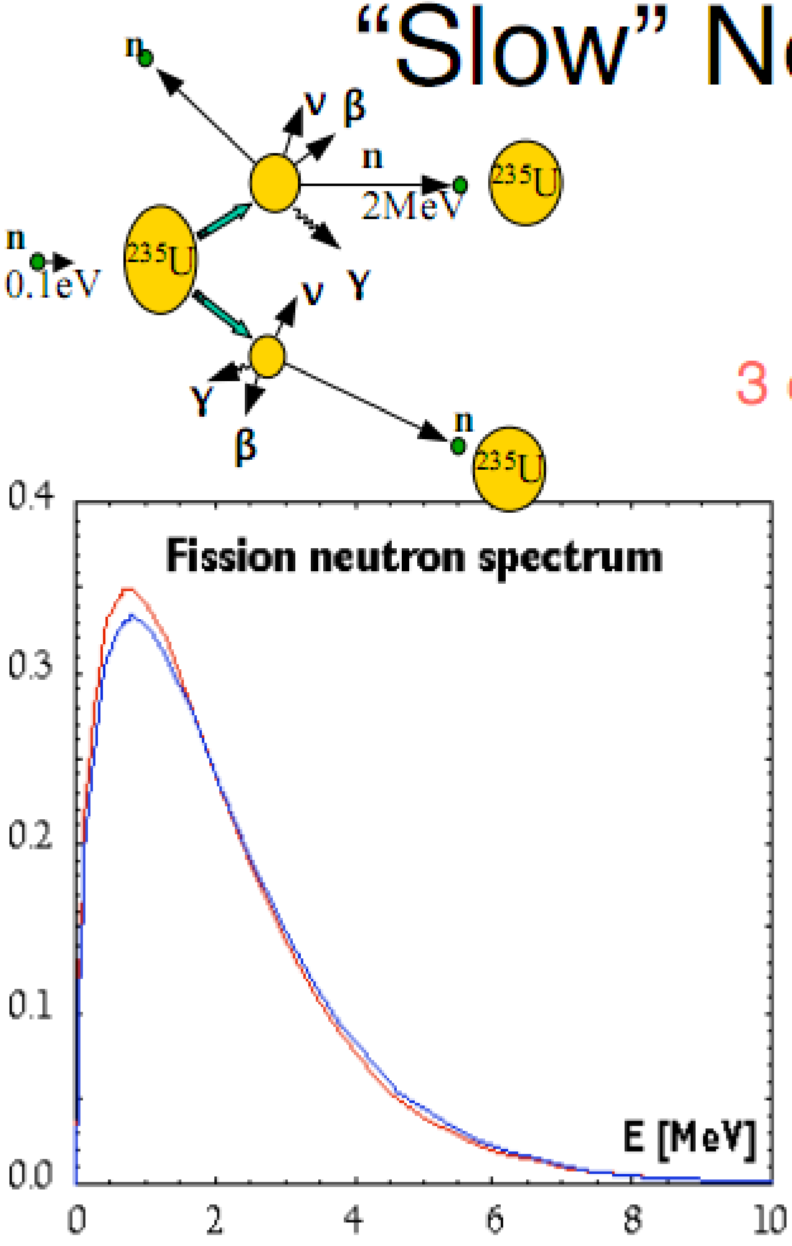
- Energy released: 200MeV/fission
- 2.5 fast neutrons per fission
- Moderator (D_2O, Graphite) required to slow fast neutrons to thermal energies
  - – H_2O with enriched ^{235}U

The Spallation Neutron Spectrum is Broad



(Courtesy,Gary Russell)

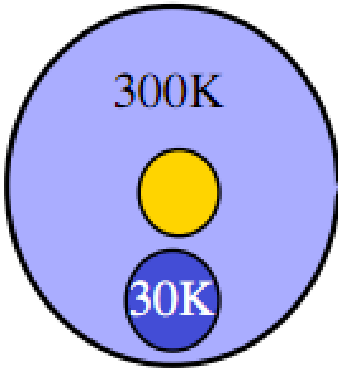
“Slow” Neutrons: MeV to neV

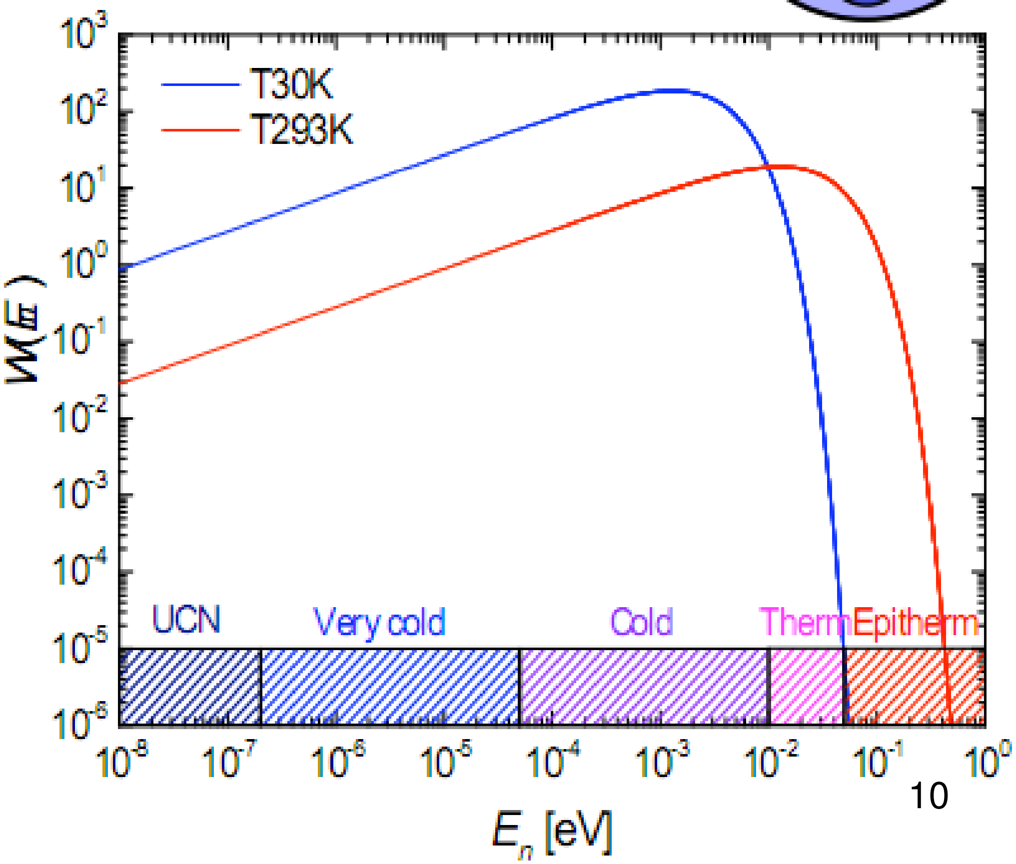


Fission neutron spectrum

Nuclear reactor

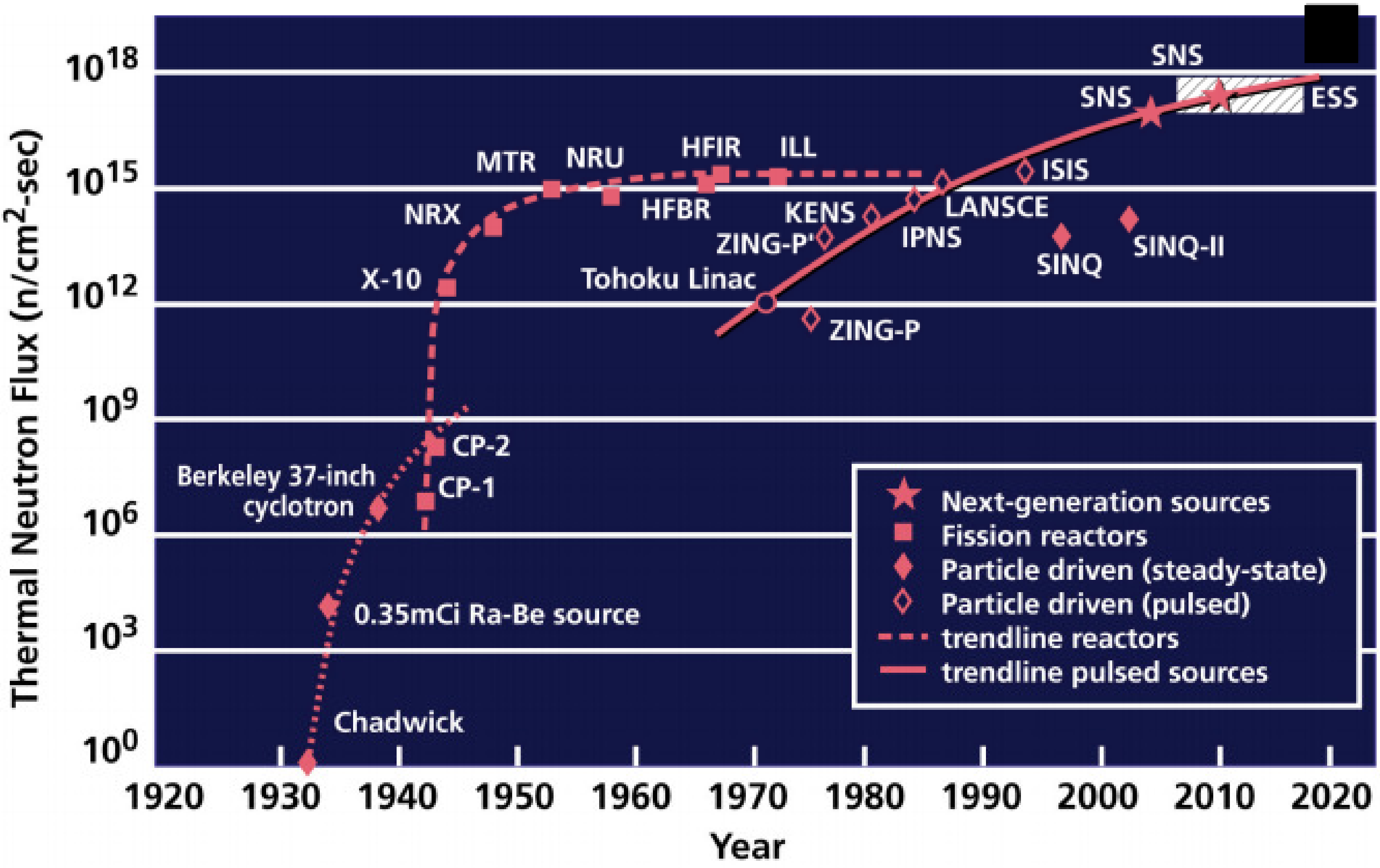
3 distinct energy regimes





M. Snow

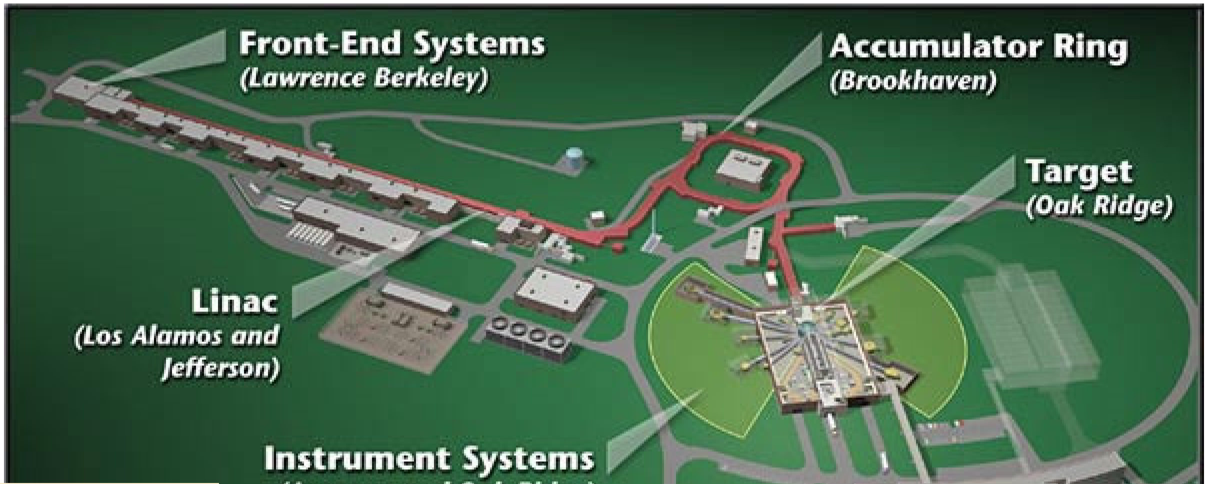
Reactors are limited by heat removal from the core
Pulsed sources have not yet reached that limit

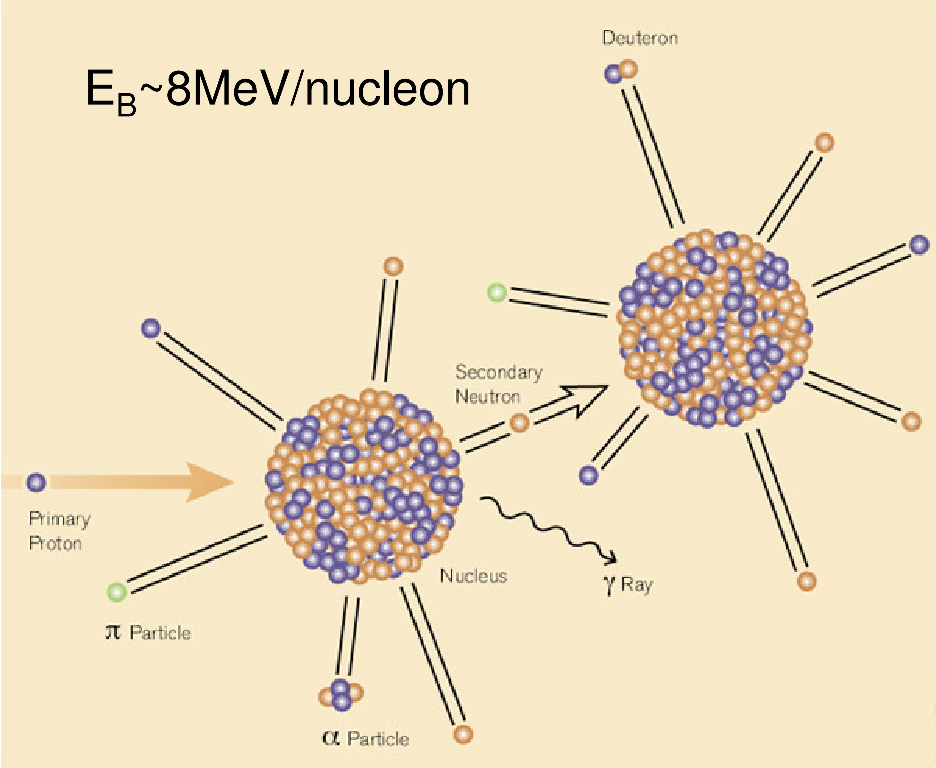


(Updated from *Neutron Scattering*, K. Skold and D. L. Price: eds., Academic Press, 1986)

Spallation Neutron Source

- IPNS, Chicago
- ISIS, England
- SINQ, Switcherland
- LANSCE, Los Alamos
- SNS, Oak Ridge





E_B~8MeV/nucleon

Spallation:

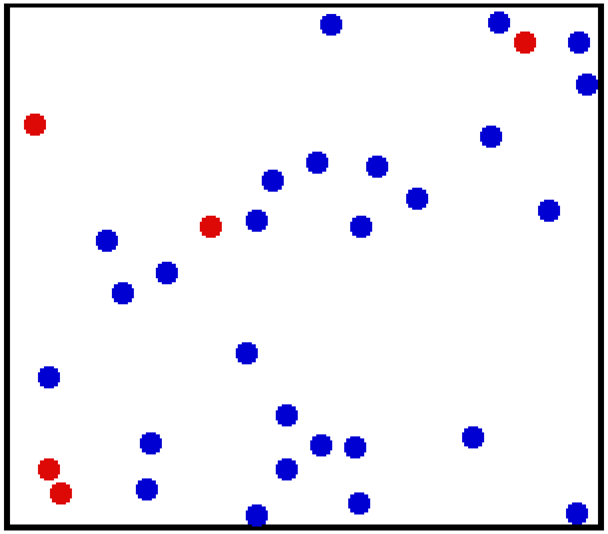
- Smash protons into a material made of heavy atomic nuclei, which contain many protons and neutrons.
- Each collision shakes loose some neutrons and other particles.
- The secondary particles hit surrounding nuclei and create even more neutrons.
- 20~30 fast neutrons / proton

Cold Sources

- are used to further thermalize thermal neutrons to lower temperatures
- Typically liquid hydrogen or deuterium operating at ~ 20K.
- Placed in the highest neutron flux possible (i.e., near the reactor core).
- Outgoing neutrons are coupled to neutron guides which “transport” the neutrons to experiments.

Neutron Moderation

Elastic Collision between neutron and proton (almost equal mass)



- Neutrons come into thermalization with the moderator material.
- In real system, thermalization is not complete, because of
  - Absorption (filter out low energy neutrons)
  - Leakage out of the source

Hydrogeneous Moderator

Neutron scattering lengths and cross sections

Isotope	conc	Coh b	Inc b	Coh xs	Inc xs	Scatt xs	Abs xs
1H	99.985	-3.7406	25.274	1.7583	80.27	82.03	0.3326
2H	0.015	6.671	4.04	5.592	2.05	7.64	0.000519

Molecular Hydrogen:

	Nuclear Spin	Ortho (more abundant) Spin	Para spin	Normal	Rotational State
H_2	½+1/2=0,1 (Fermi stat.)	1 (sym)	0 (anti-sym)	3/(3+1)=75% ortho	Odd J
				1/(3+1)=25% para	Even J (J=0, ground state)
D_2	1+1=0,1,2 (Bose stat.)	0,2 (sym)	1 (anti-sym)	6/(6+3)=66% ortho	Even J (J=0, ground state)
				3/(6+3)=33% para	Odd J

Liquid Hydrogen

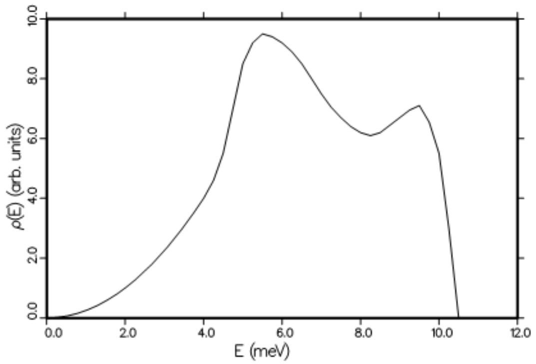


Figure 81: The Keinert-Sax frequency distribution for the effective translational modes of liquid hydrogen.

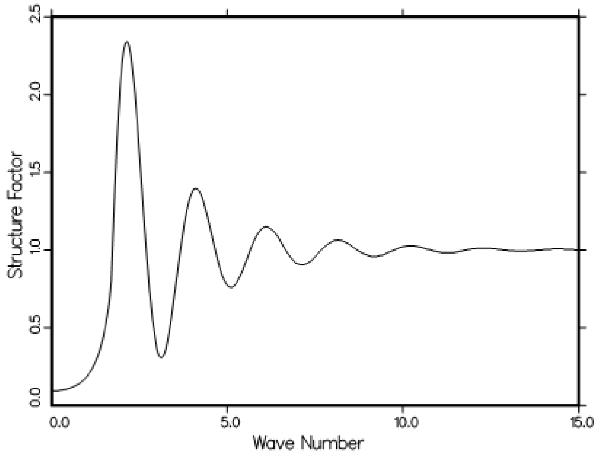
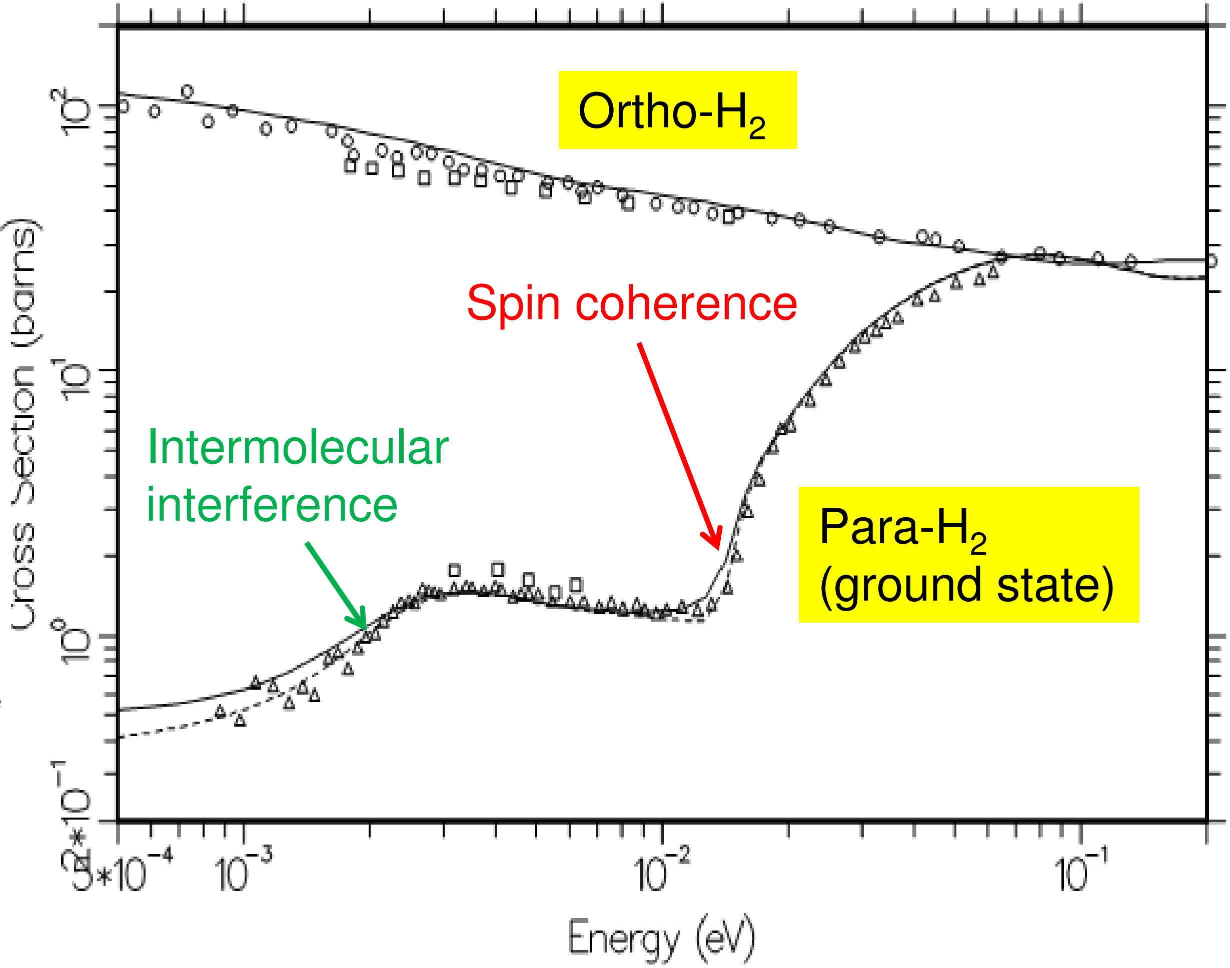


Figure 82: The static structure factor $S(\kappa)$ for liquid hydrogen.



Ortho-H_2

Spin coherence

Intermolecular interference

Para-H_2 (ground state)

Figure 91: The cross sections for liquid ortho hydrogen (upper curve) and liquid para hydrogen (lower curve) are compared with experimental data (see Ref. 29) obtained by Squires (gas) at 20 K (squares), Whittemore at 20 K (circles), and Seiffert at 14 K (triangles). The solid curves are at 20 K, and the dashed curve is at 14 K. The sharp drop in the para cross section below 0.05 eV is due to spin coherence, and the second drop below .003 eV is due to intermolecular interference.

Application to cold neutron moderation

- The main energy transfer mechanism for neutrons at low energies is the para to ortho spin-flip transition, where the neutron losses energy of 14.7 meV.

- Ortho/para ratio depends on the beam power.
  - Conversion towards ground state para-H_2.
  - Radiations create excited ortho-H_2 state.

Liquid Deuterium

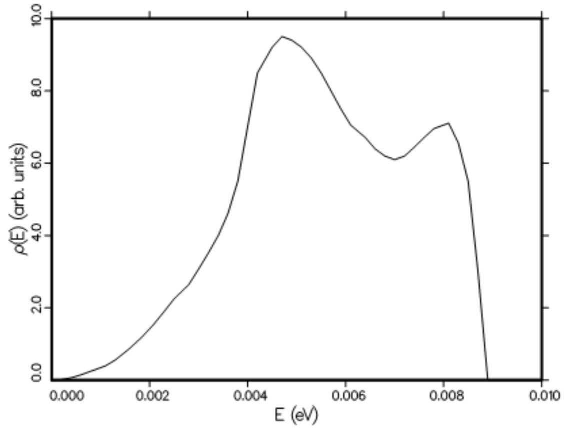


Figure 94: The Keinert-Sax frequency distribution for the effective translational modes of liquid deuterium.

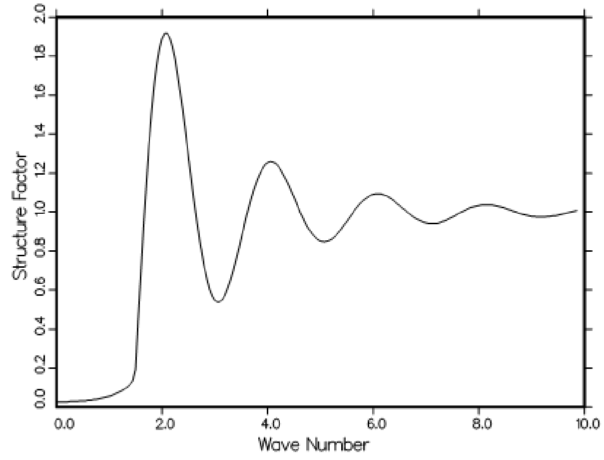
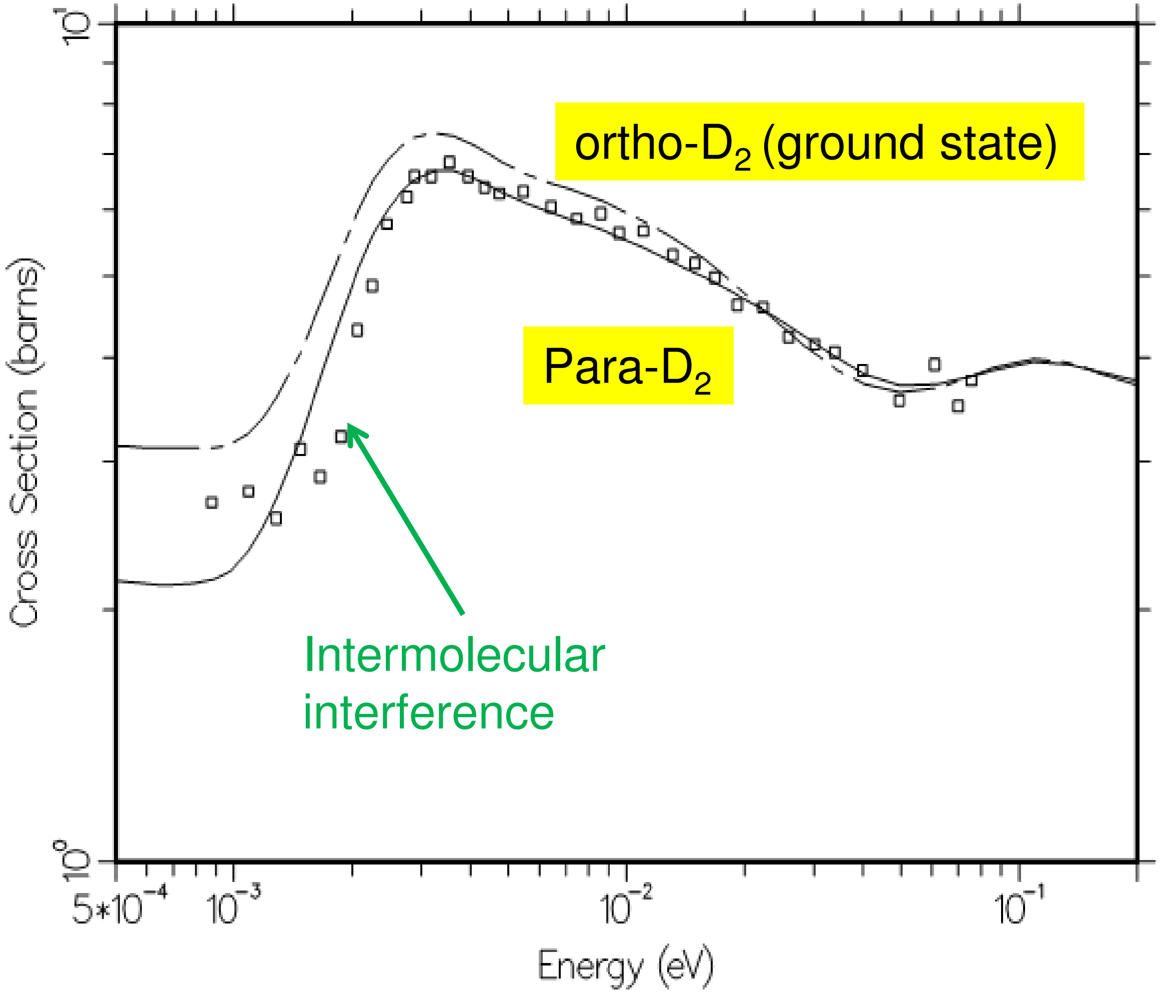


Figure 95: The static structure factor $S(\kappa)$ for liquid deuterium.



ortho-D_2 (ground state)

Para-D_2

Intermolecular interference

Figure 104: The cross sections for liquid para deuterium (solid curve) and liquid ortho deuterium (chain-dash curve) at 19 K are compared with experimental data of Seiffert for an equilibrium ortho-para mixture at 19 K (see Ref. 30). The drop in the cross sections below .003 eV is due to intermolecular interference.

R. E. MacFarlane, "New Thermal Neutron Scattering Files for ENDF/B-VI Release 2," Los Alamos National Laboratory report LA-12639-MS (ENDF 356) (March 1994)

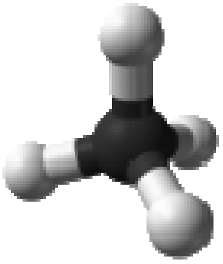
Common moderators

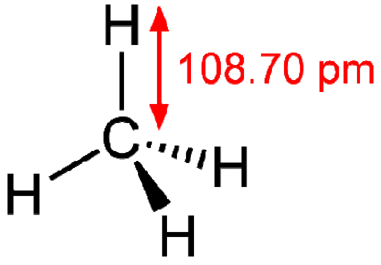
Glasstone and Edlund (1952)

Property	Symbol	H_2O	D_2O	Be	C
Mean lethargy increment	ξ	0.920	0.509	0.209	0.158
Diffusion length (cm)	L	2.88	100	23.6	50.2
Diffusion time (s)	t_d	3.1×10^{-4}	0.15	4.3×10^{-3}	1.2×10^{-4}
Albedo	β_∞	0.821	0.968	0.889	0.930
Slowing-down length (cm)	L_s	5.7	11.0	9.9	18.7
Slowing-down time(s)	t_s	10^{-5}	4.6×10^{-5}	6.7×10^{-5}	1.5×10^{-4}
Migration Length(cm)	M	6.4	101	25.6	53.6

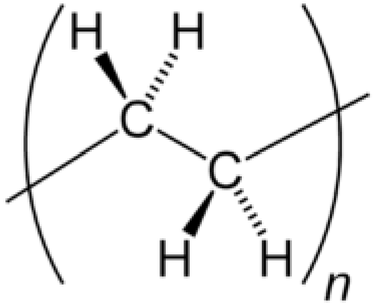
Other Hydrogeneous Moderators

- Solid Methane
  - – CH_4
  - – CD_4





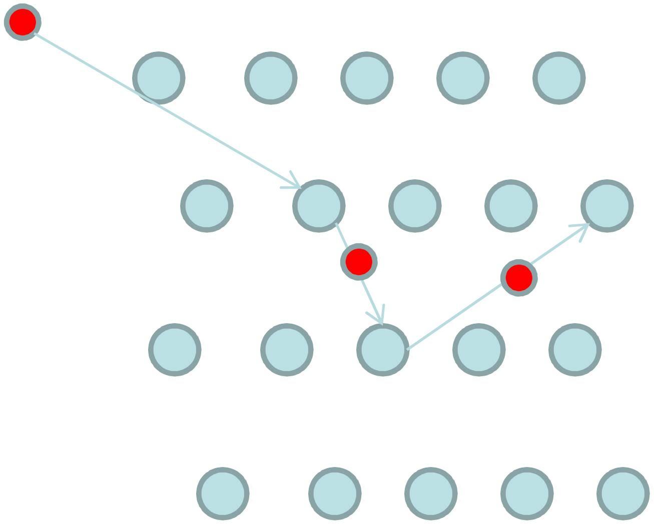
- Polyethylene (High Density)
  - – $(CH_2)_n$



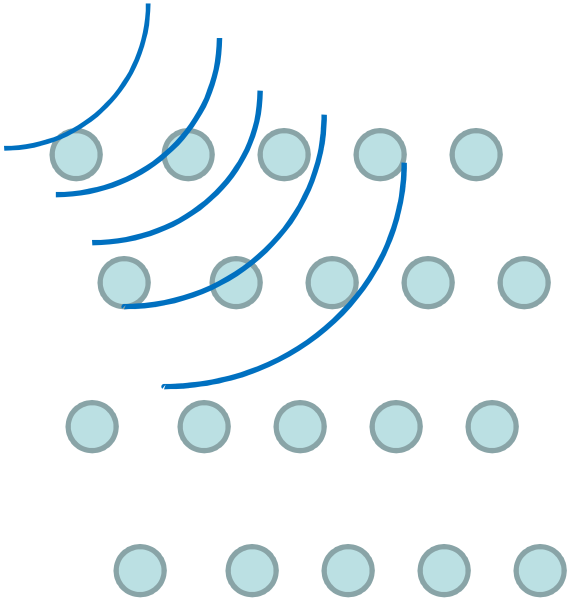
- ZrH_2
  - – used in TRIGA reactors

Fermi Pseudo-Potential

Fast Neutrons
(particle pictures)



Slow Neutrons
$\lambda_n \approx a$



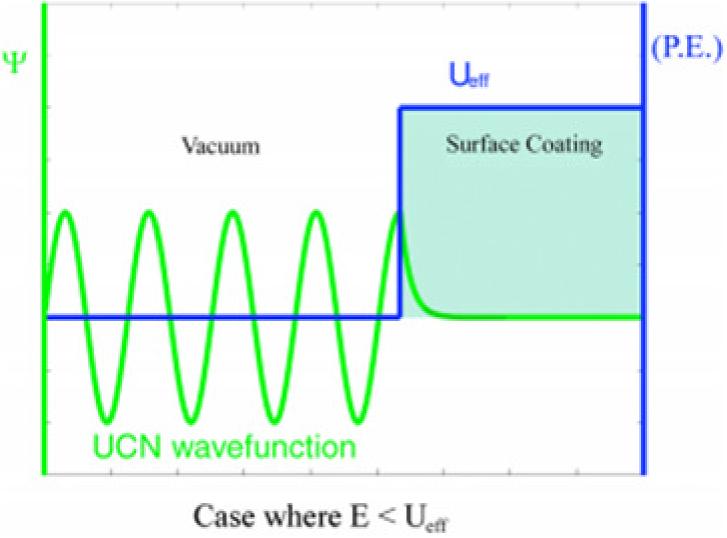
$$V = \frac{2\pi\hbar^2}{m_n}\overline{\sum_i b_i \delta\left(r - r_i\right)} = \frac{2\pi\hbar^2}{m_n} b_{coh}\rho$$

One Dimensional Quantum Physics

For E>U_{eff}

$$R=\left(\frac{k_0-k}{k_0+k}\right)^2 \quad , \quad T=1-R=\left(\frac{2k_0}{k_0+k}\right)^2$$

For E<U_{eff}



Case where E < U_{eff}

$$\psi(x)=e^{ik_0x}-e^{2i\delta-ik_0x}$$ For x <0

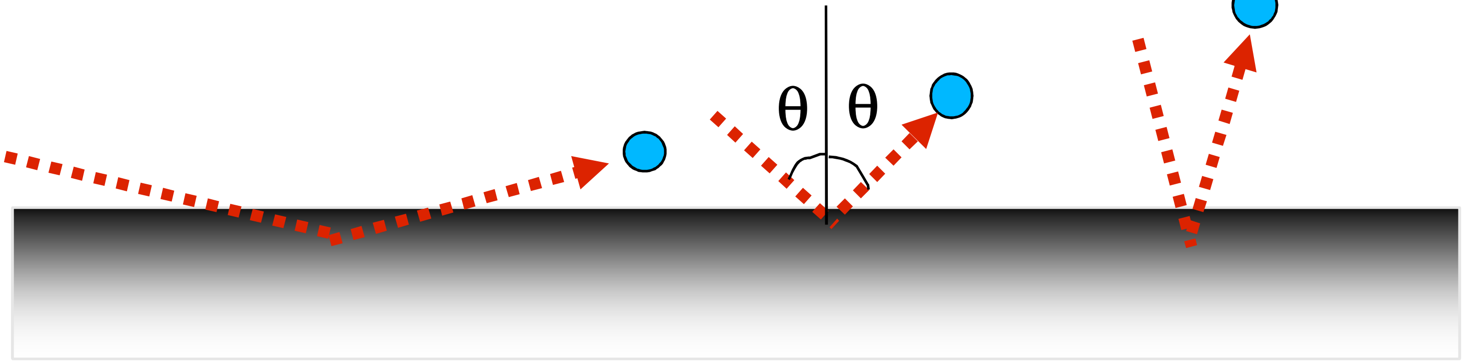
$$\psi(x)=(1-e^{2i\delta})e^{-kx}$$ For x > 0

$$\cos\delta = k\Big/\sqrt{k_0^{\ 2}+k^2}$$

$$R=1 \quad , \quad T=1-R=0$$

Ultracold Neutrons (UCN)

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



Total reflection at all incident angles!

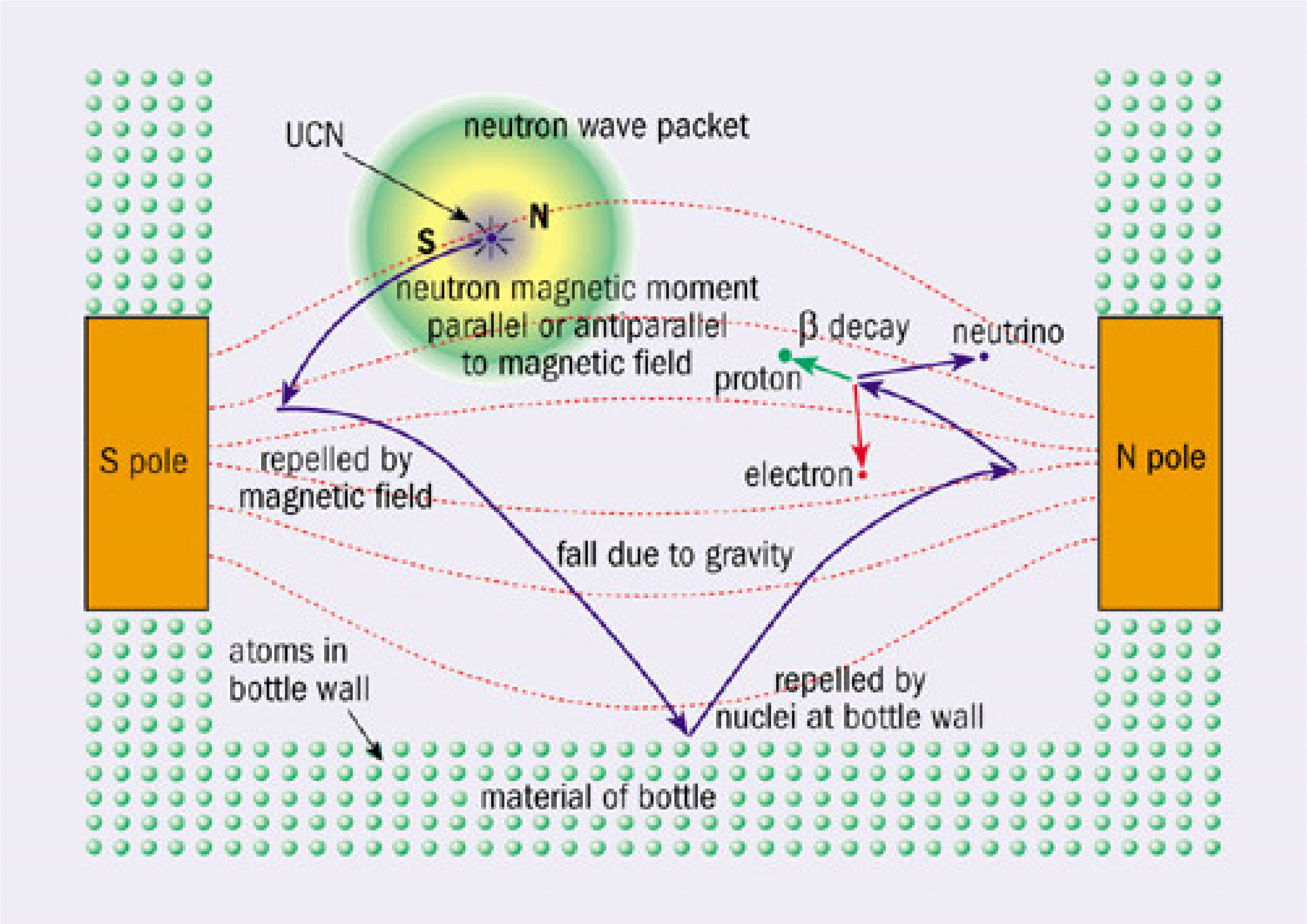
Material Potential

$$v_c = \sqrt{\frac{2V_F}{m_n}} = \frac{2\pi\hbar}{m_n}\sqrt{\frac{Nb}{\pi}}$$

Material	V_F(neV)	v_c (m/s)	η ($\times 10^{-4}$)
D_2O	170	5.6	
Be (BeO)	250	6.9	2.0-8.5
C	180	5.8	
Mg	60	3.4	
Al	50	3.2	2.9-10
SiO_2 (quartz)	110	4.6	
Cu	170	5.6	2.1-16
Fe	220	6.5	1.7-28
Co	70	3.7	
Ni	230	6.8	5.1

Fermi Potential Under Fields

$$V_F = \frac{2\pi\hbar^2 Nb}{m_n} \pm \vec{\mu}_n \cdot \vec{B} + m_n g h$$



±60neV per 1T

-100 neV per meter rise

+100 neV per meter drop

UCN Transport

- Not 100%
  - Loss at boundary between vacuum and medium due to capture or inelastic scattering.
- Weakly absorbing medium with a total cross-section σ_t
  - Loss per bounce:

$$\mu = \int_0^\infty N\sigma_t |\psi(x)|^2 dx = \frac{2N\sigma_t}{k}\sin^2\delta$$

Optical theorem: $\sigma_t = \frac{4\pi \operatorname{Im} f(0)}{k} = -\frac{4\pi}{k_0}\operatorname{Im}(b)$

$$\mu = -\frac{\operatorname{Im}(b)}{\operatorname{Re}(b)}\frac{2v}{\sqrt{v_c{}^2 - v^2}} \qquad \bar{\mu} = 2\int \mu(\theta_i)\cos\theta_i d(\cos\theta_i)/4\pi$$

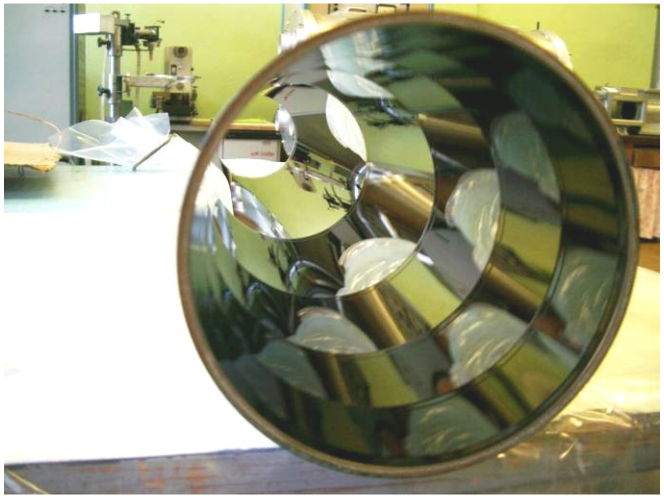
~ 10^{-5}-10^{-4}

- Anomalous loss: surface contaminants, non-uniformity

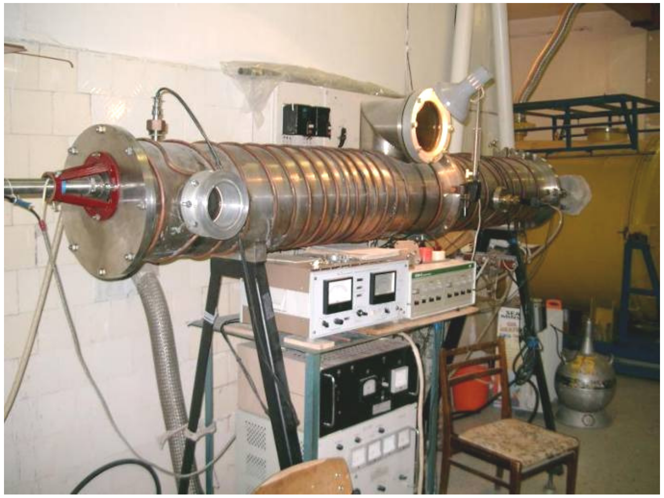
UCN guide with a big diameter (anodomechanical technology)

Installations for the final stage of polishing

High polished stainless steel tube with a diameter of 150 mm



Installation for $Ni^{58}Mo$ coating inside the tube

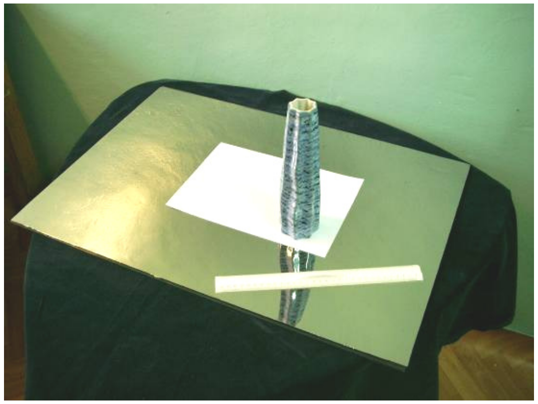


Courtsey, A. Serebrov

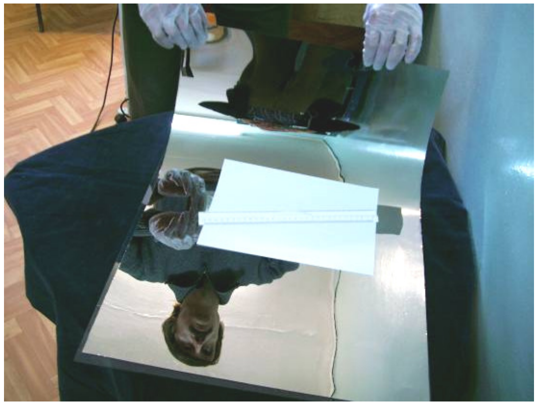
UCN guide with a big diameter (replica technology)

Installation for coating of $Ni^{58}Mo$ on the float glass

Courtsey, A. Serebrov



foil after separation
from glass
(size 700x470 mm^2)



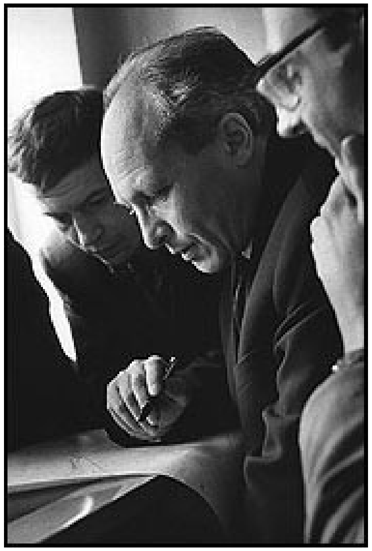
preparation of
a UCN guide

UCN guides of
different diameters

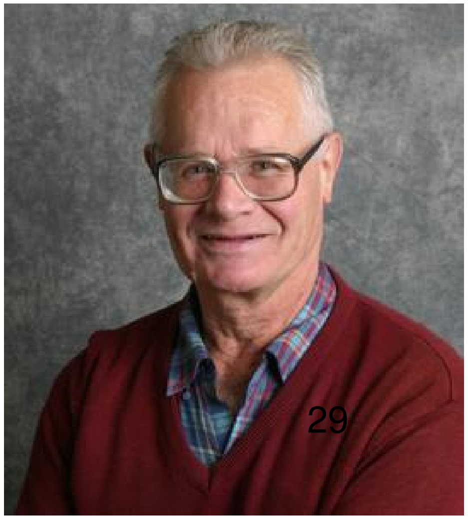
Brief History of UCN

- Neutron discovered in 1932 – Chadwick

- Concept of UCN was probably realized by Fermi, but Zeldovich was the first to take it seriously enough to put it input print (1952).



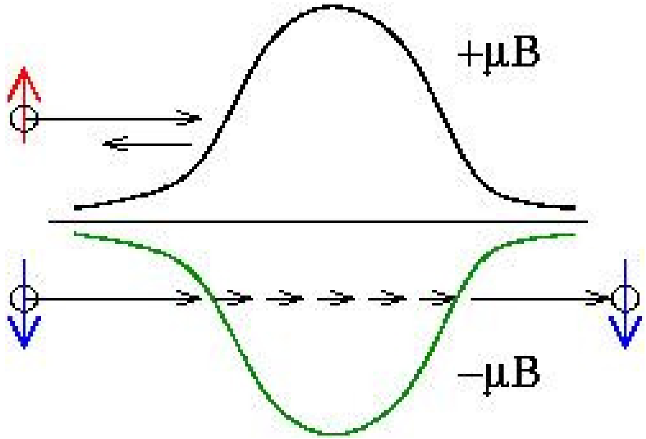
- Vladimirskii (1961) proposed magnetic focusing.



- First observed by Shapiro (1969) at JINR (Dubna) and independently by Steyerl at FRM in Munich.

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 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**

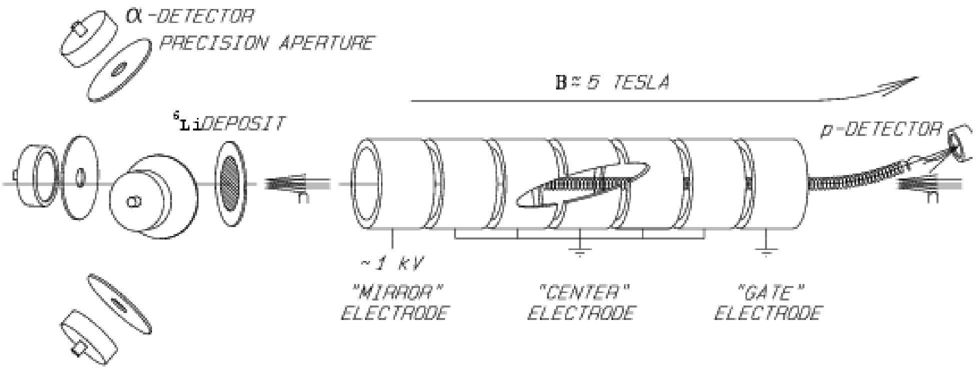
  T reversal symmetry & CP violation extensions to the standard model.

- **N-Nbar oscillation search**

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

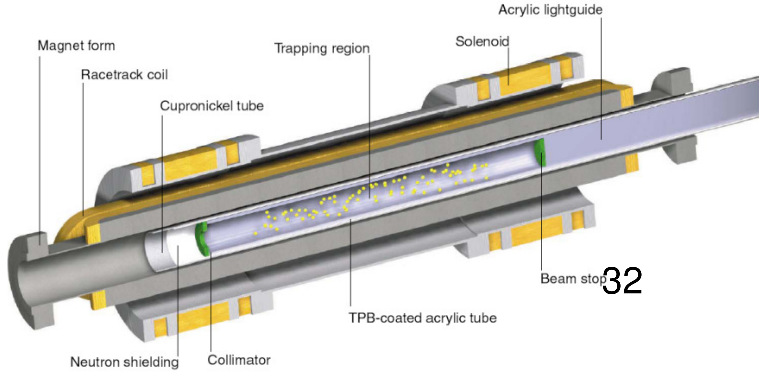
Motivated by the observed baryon asymmetry of the universe.

Neutron β-decay

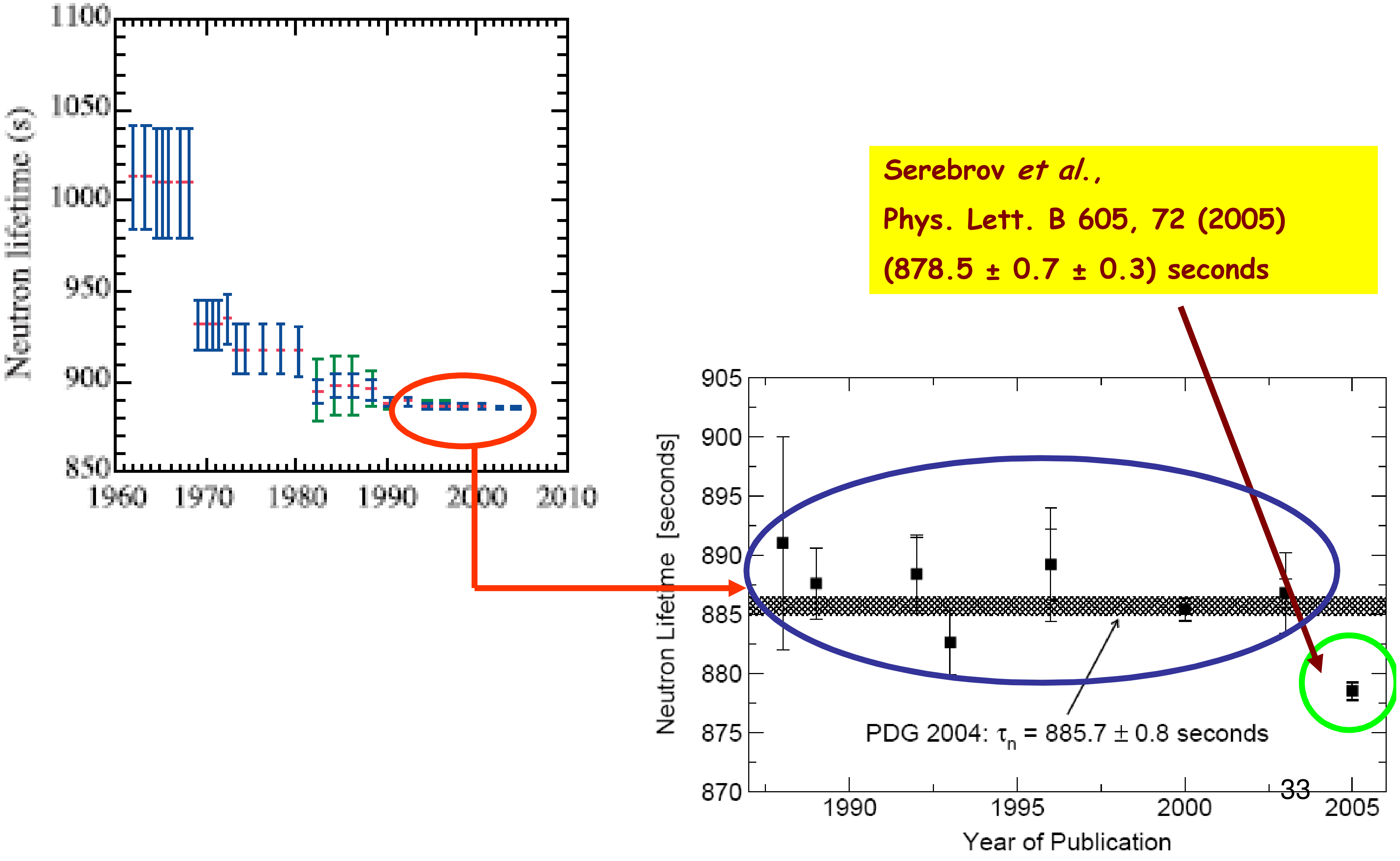


Lifetime

- Cold Neutron beam experiments: $\tau_\beta = N_0 / N_d$
  - Absolute measurements of the neutron number and the decay particle flux.
- Bottled UCN: $N(T) = N_0 e^{-T/\tau_\beta} \Rightarrow \tau_\beta = T \big/ \ln(N_0 / N(T))$
  - 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 (833^{+74}_{-63}s).
    - Statistically limited.



Progress of Neutron Lifetime Measurements

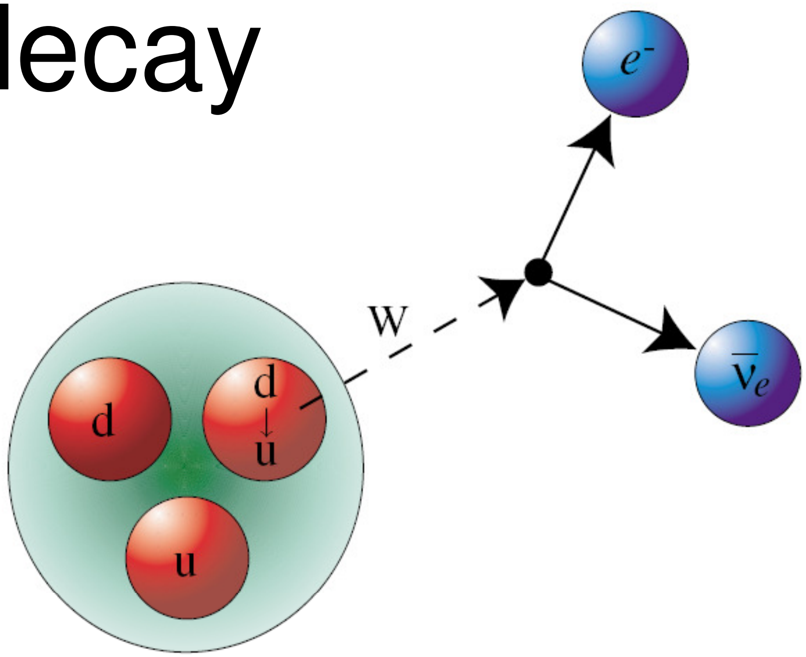


Serebrov *et al.*,

Phys. Lett. B 605, 72 (2005)

(878.5 ± 0.7 ± 0.3) seconds

Neutron decay



V-A weak interaction

$$H_\beta = H_{V,A}$$
$$= \bar{e}\gamma_\lambda(1-\gamma^5)\nu_e \bar{p}(g_V + g_A\gamma^5)\gamma^\lambda n$$

$$n \longrightarrow p^+ + e^- + \bar{\nu}_e + 782\text{ keV}$$

J. D. Jackson, S.B. Treiman, H.W. Wyld, Jr,
Phys. Rev. 106, 517 - 521 (1957)

$$d\Gamma \propto p_e E_e (E_0 - E_e)^2 dE_e d\Omega_e d\Omega_\nu$$
$$[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + P_n\left[A\frac{\vec{p}_e \cdot \vec{\sigma}}{E_e} + B\frac{\vec{p}_\nu \cdot \vec{\sigma}}{E_\nu} + D\frac{\vec{\sigma}\cdot(\vec{p}_e \times \vec{p}_\nu)}{E_e E_\nu}\right]$$

Asymmetry in angular correlations

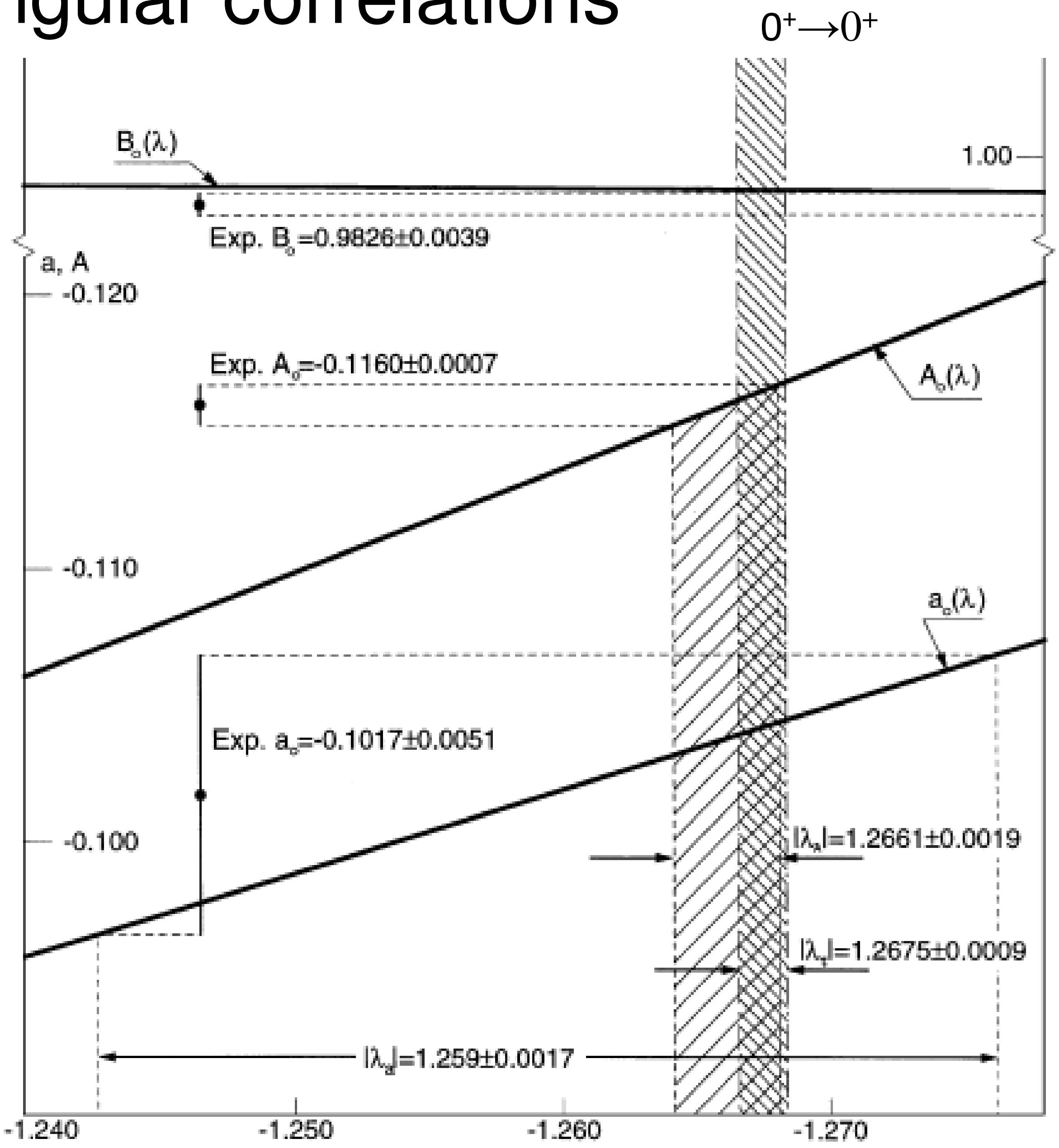
In SM, V-A interaction

$$a = \frac{1-\lambda^2}{1+3\lambda^2}, \quad b = 0$$

$$A = -2\frac{\lambda^2+\lambda}{1+3\lambda^2}, \quad B = 2\frac{\lambda^2-\lambda}{1+3\lambda^2}$$

$$D = 2\frac{\mathrm{Im}(\lambda)}{1+3\lambda^2}$$

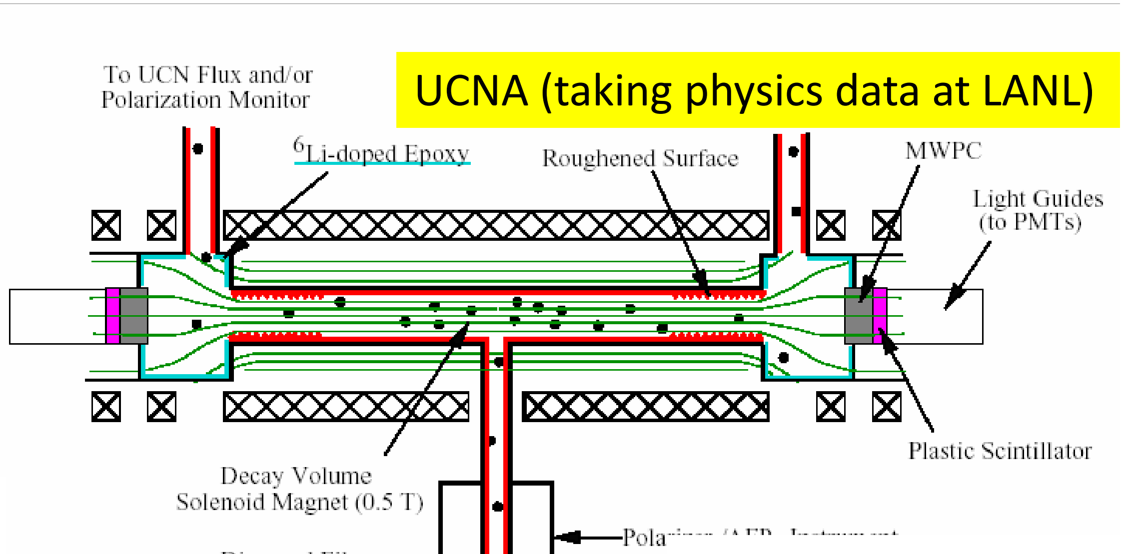
λ: an important parameter to
Input into the solar neutrino
estimates

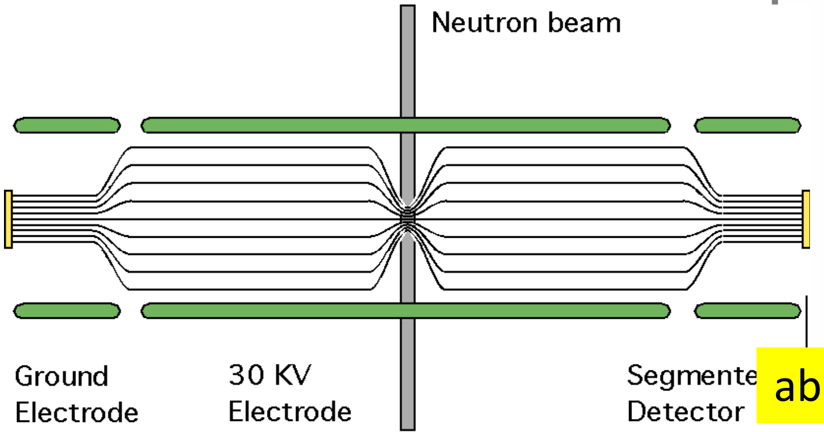


Yerozolimsky, NIMA 2000

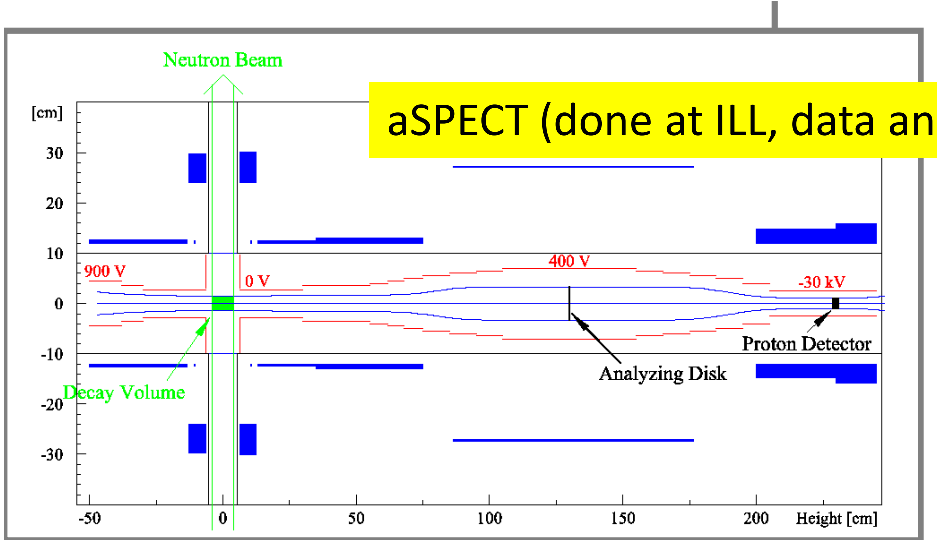
Angular correlation experiments

UCNA (taking physics data at LANL)

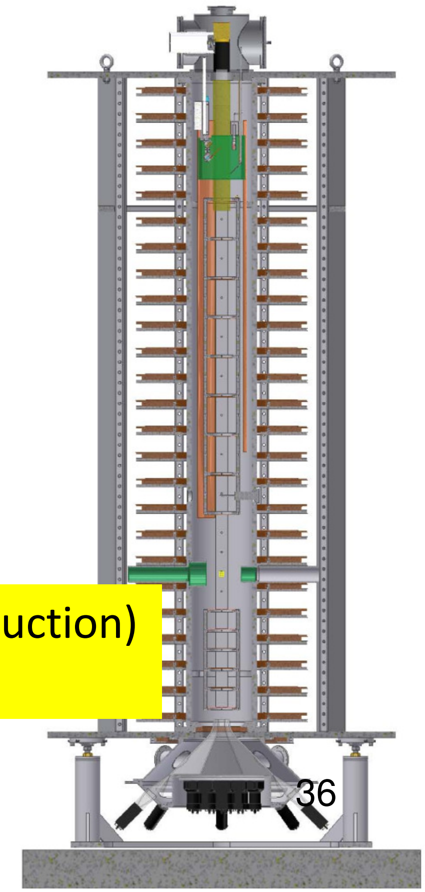




abBA, Nab, PANDA (planned at SNS)



aSPECT (done at ILL, data analysis)



aCORN (in construction)
Run at NIST

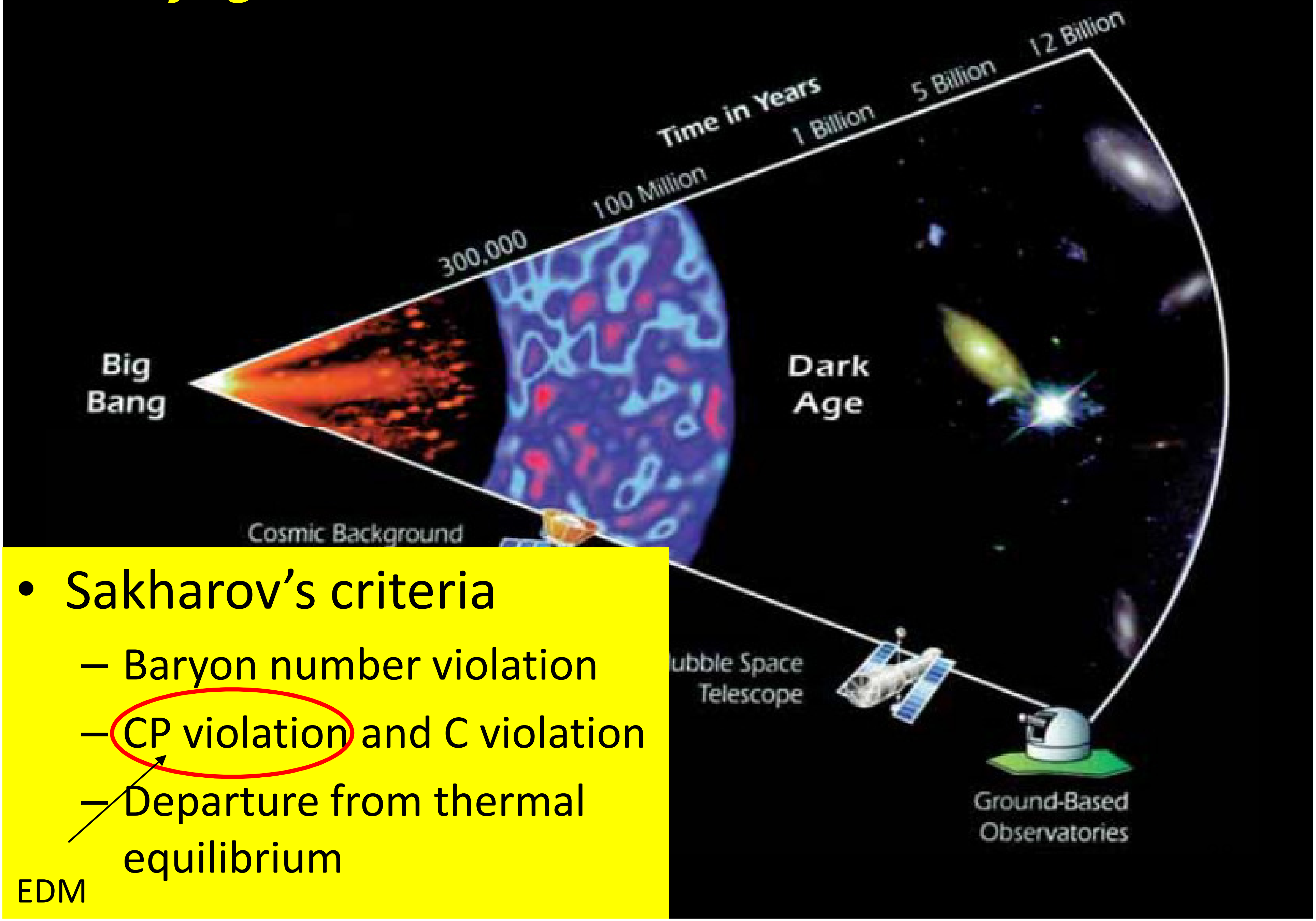
Measuring Zero –
New Era of Exotic Interactions

- P-odd, T-odd moment
  - Permanent Electric Dipole Moment (EDM) search
  - Put the most stringent limits on many T reversal symmetry violation extensions to the Standard Model.

- Baryon number violation
  - N-Nbar oscillation
  - Proton decay

Both are motivated to explain the observed Baryon Asymmetry of the Universe.

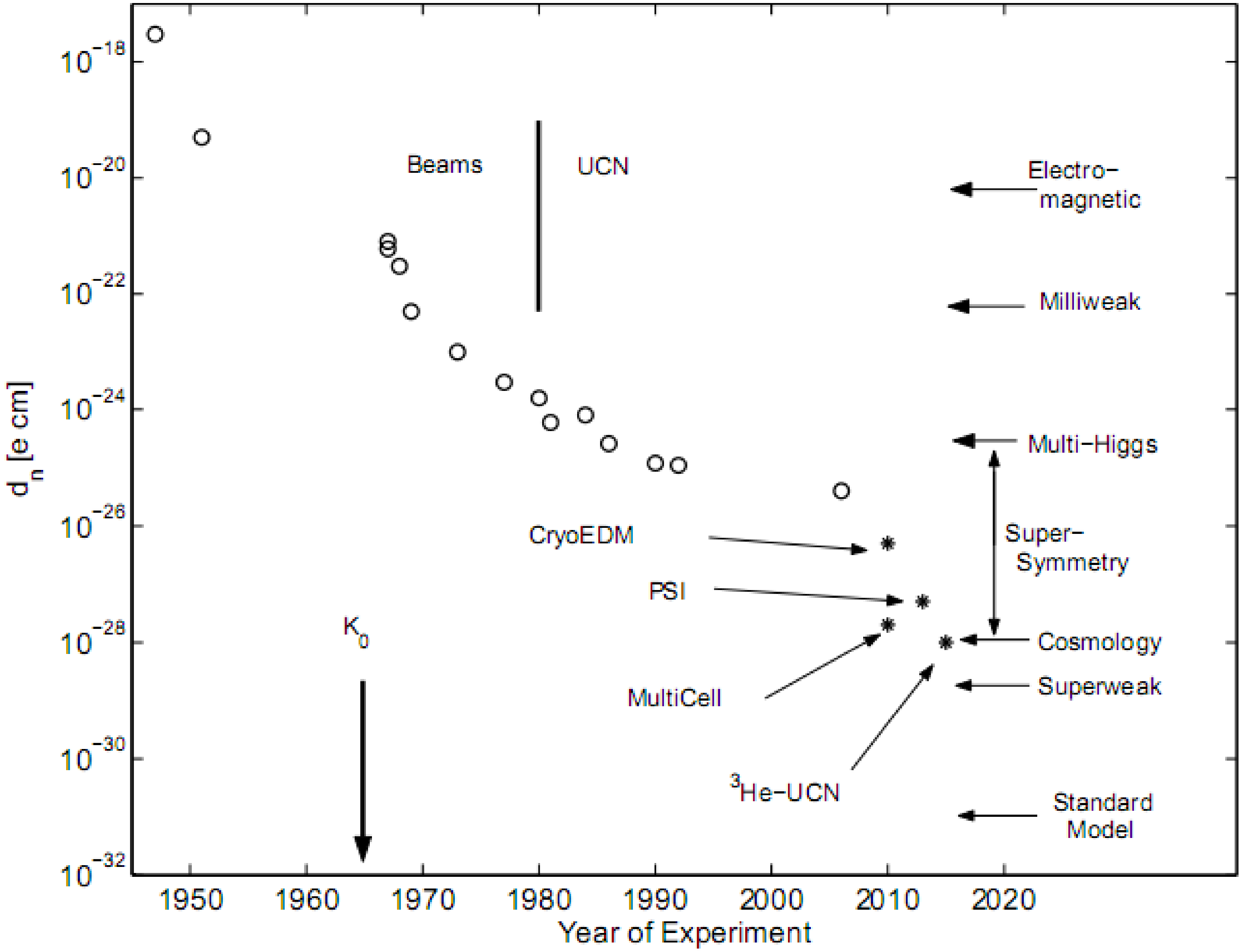
Baryogenesis created more matter than anti-matter



- Sakharov’s criteria
  - Baryon number violation
  - CP violation and C violation
  - Departure from thermal equilibrium

EDM

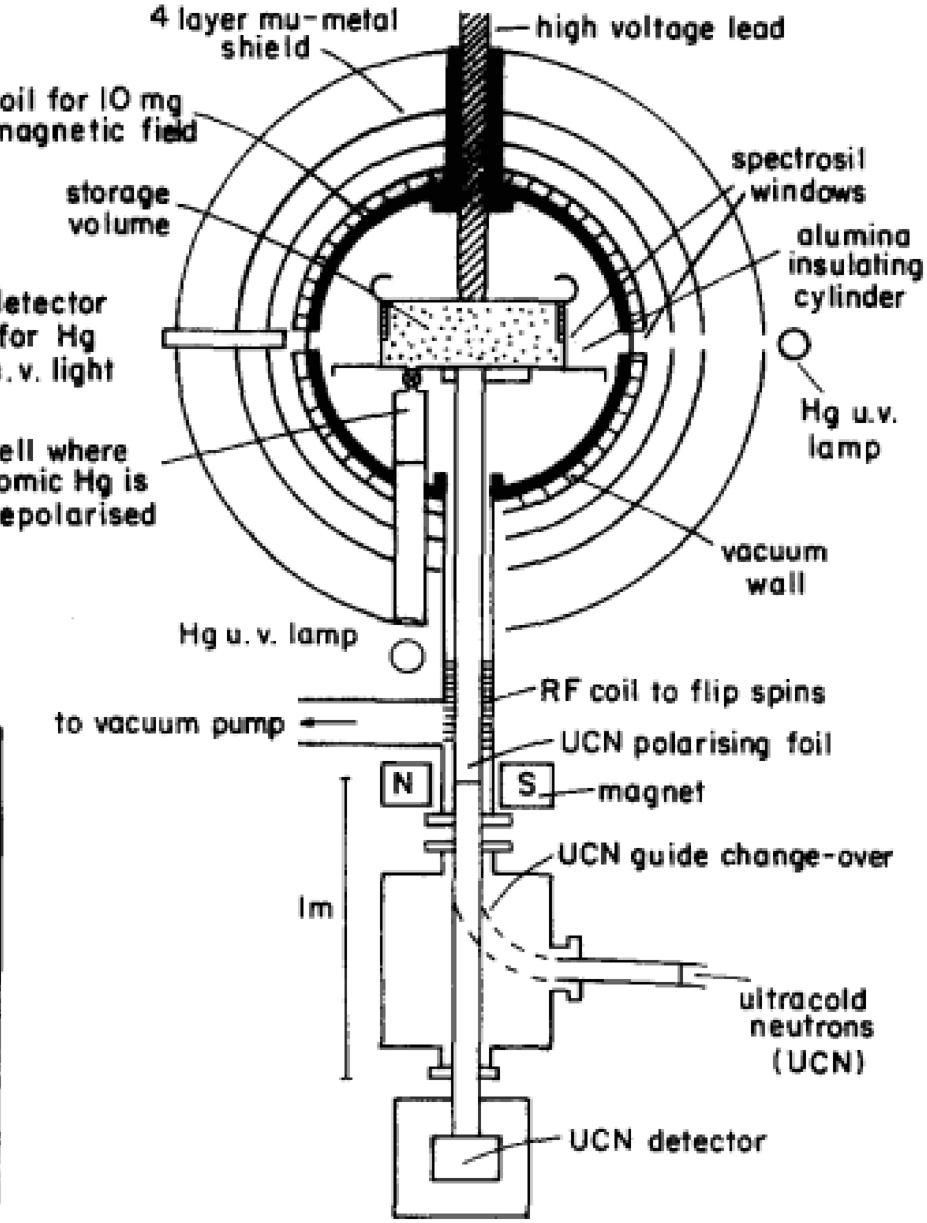
Search for Neutron EDM

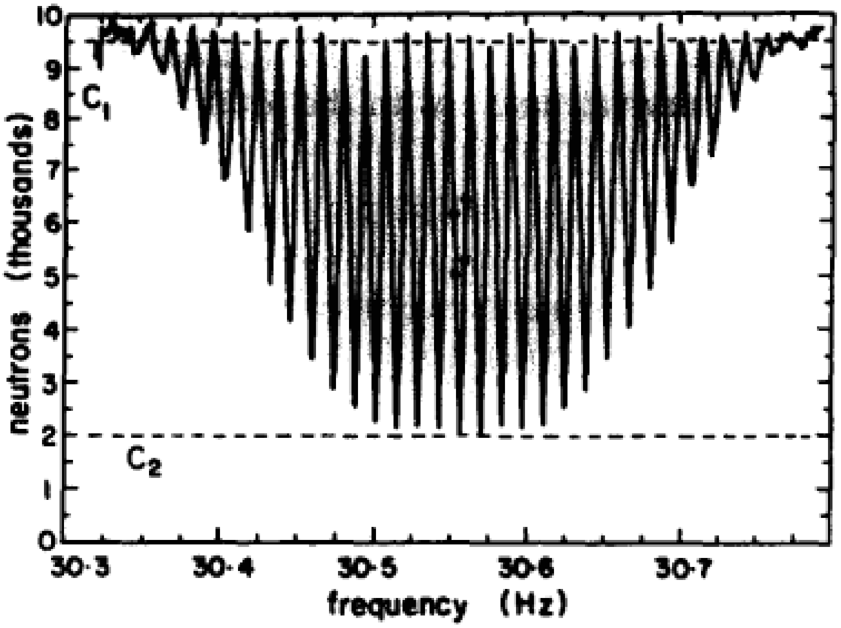


ILL Experiment:

- UCN in storage cell (Be electrode, BeO dielectric cell wall) at room temperature

- Ramsey's separate oscillatory field method (interference in time domain)





Traditional technique: Nuclear Magnetic Resonance

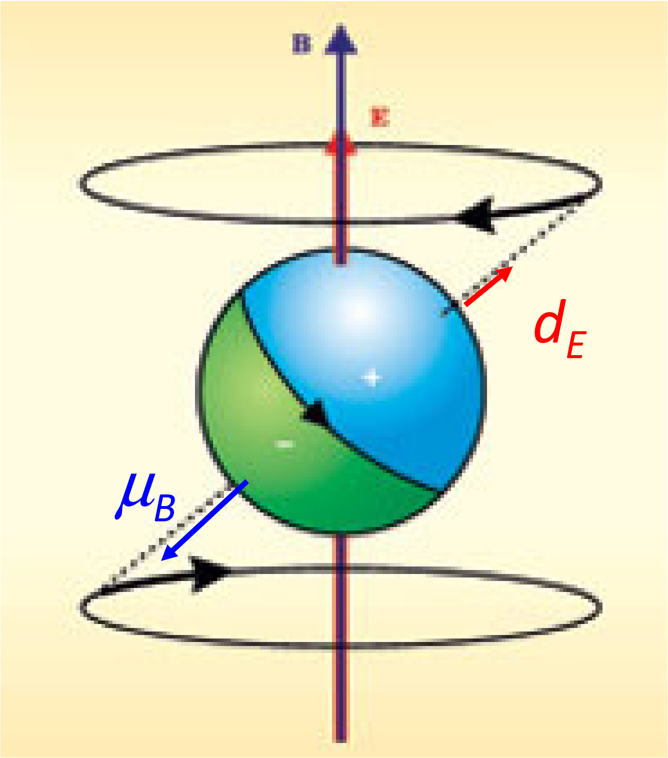


Figure: Physics Today 56 6 (2003) 33

$$H = -\left(\mu\vec{B} + d_n\vec{E}\right)\cdot\frac{\vec{S}}{|S|}$$

- Larmor frequency: $\omega_B = -\frac{2\mu_B B}{\hbar}$

(~ 50 Hz for *B* ~ 0.1G)

- d_n: additional precession: $\omega_E = \frac{2d_n E}{\hbar}$

$$\omega_{E\parallel B} - \omega_{E\,anti-\parallel B} \equiv \boxed{\Delta\omega = \frac{4d_E E}{\hbar}}$$

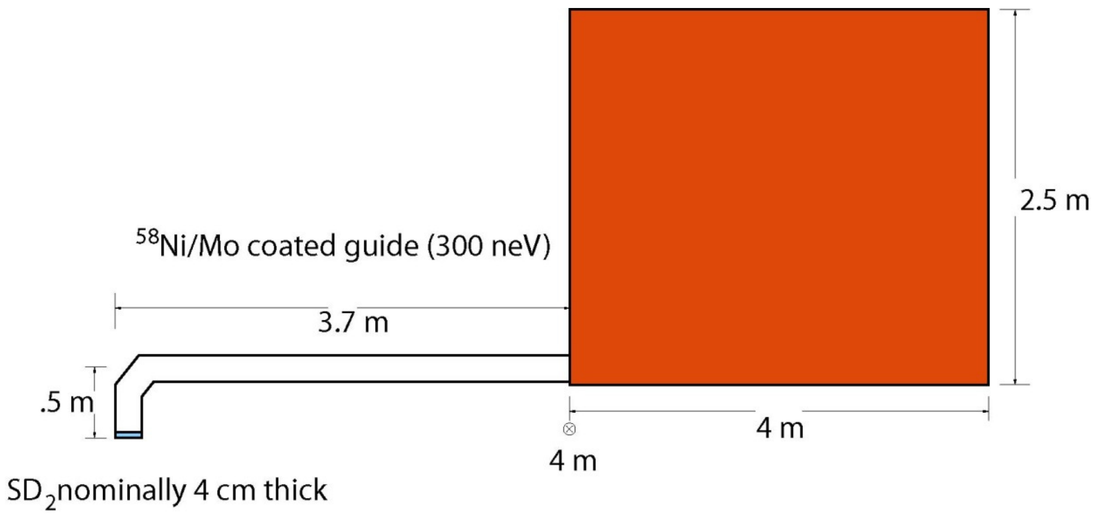
- Apply static *B*, *E*||*B*

- Look for $\Delta\omega$ on reversal of *E*

Nnbar Oscillation

- Current limit: τ_{nnbar}> 8.6×10^7 s (free n), 1.2×10^8 s (bound n)
- New theoretical prediction: 10^{10} s

B. Dutta, Y. Mimura, R.N. Mohapatra, PRL 96, 061801 (2006).



- Evaluated idealized geometry & conclusion:
- UCN rate > 5.7 ×10^7 UCN/s for 3 years to reach τnnbar >10^9 s

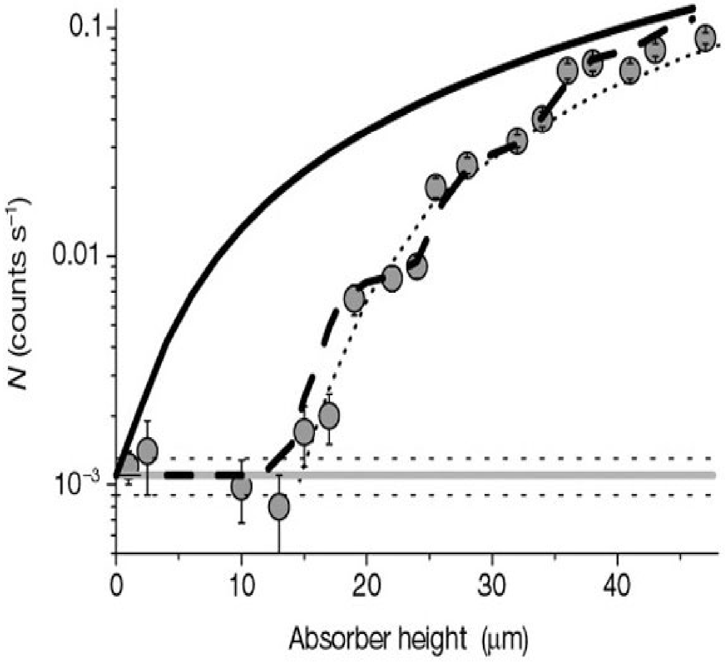
- Need more UCN → Source R&D

Courtesey, A.R. Young

UCN Quantization under Gravity

V.V. Nesvizhevsky, et al., Nature **415**, 297(2002)

- Quantization of neutron wave-function in the gravitational field of earth.
  - Because of the small scale of the gravitational force (relative to E&M and nuclear force), observation of such effect is extremely challenging.
- Energy ~ peV.
  - 10 μm against gravitation on earth.



Technical Challenges with Experiments using UCN:

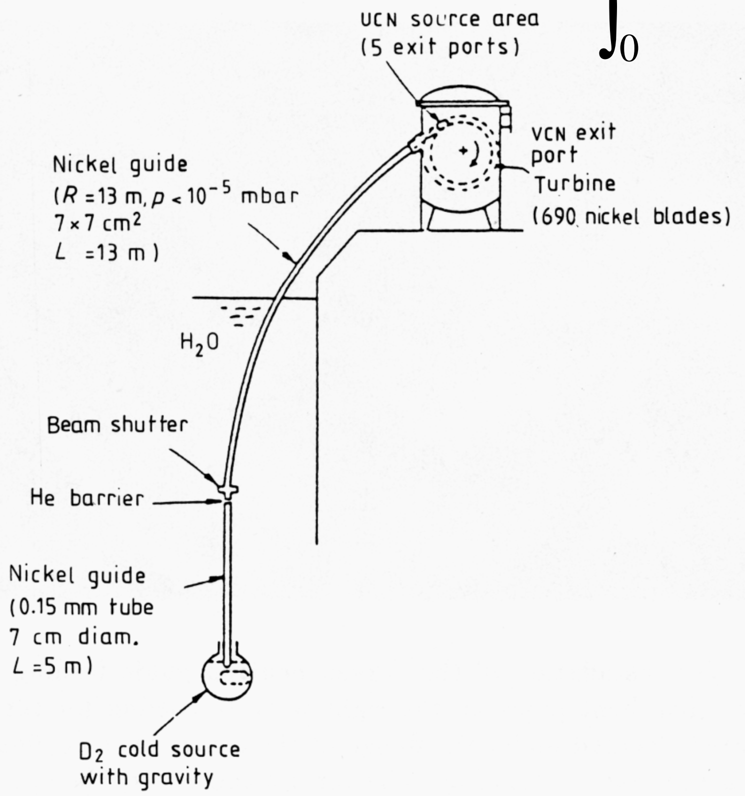
Need more UCN flux!

UCN in Thermal Spectrum

- Thermal Neutron Flux: $\varphi_T(E_n)dE_n = \varphi_0 e^{-E_n/kT} \frac{E_n}{kT} d\left(\frac{E_n}{kT}\right)$

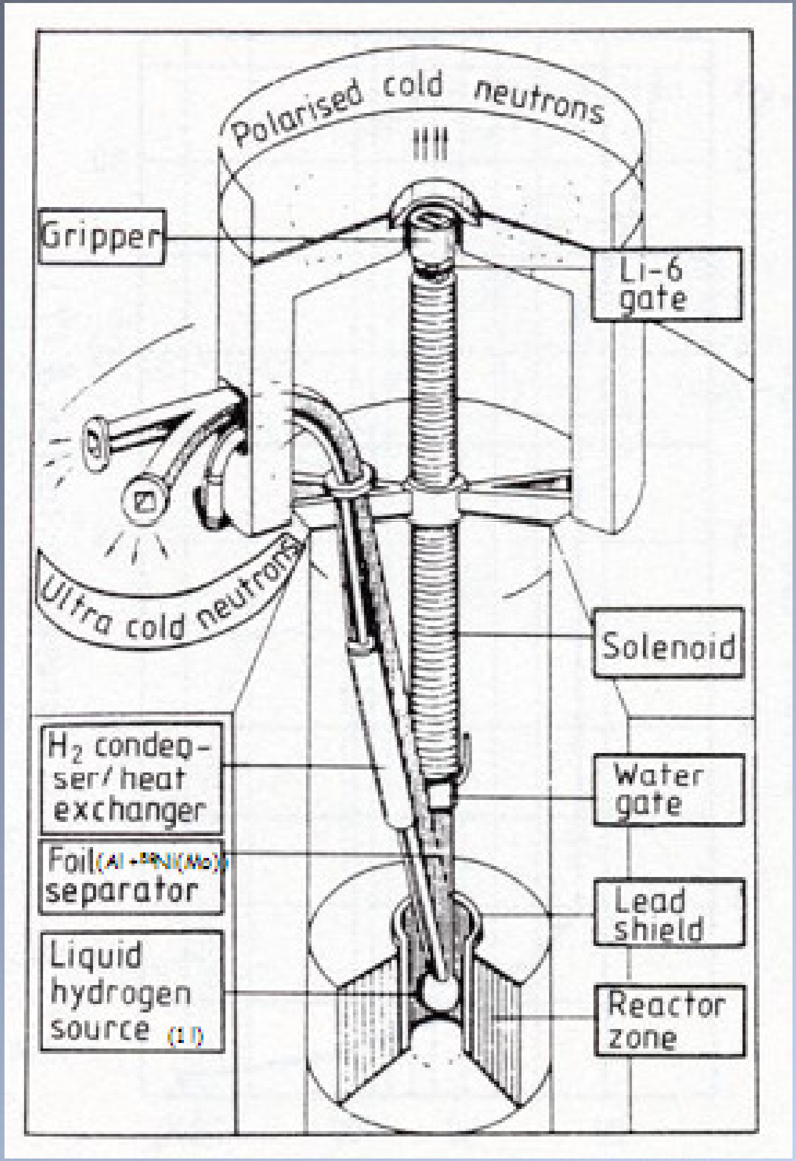
UCN fraction: $\int_0^{300neV} \varphi_T(E)dE \Big/ \varphi_0 \approx 10^{-11}$ with 300K thermal flux

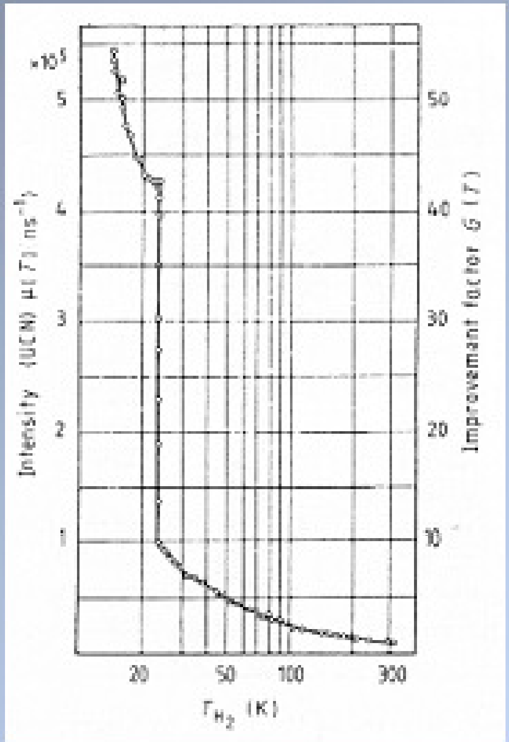
$\int_0^{300neV} \varphi_T(E)dE \Big/ \varphi_0 \approx 10^{-9}$ with 20~30K cold flux



- UCN (100neV) and VCN (100μeV) (*fundamental particle physics*)
  - Gravitational deceleration
  - Turbine deceleration (ILL source)
  - Superthermal UCN converter

Source of polarized cold and UCN at PNPI



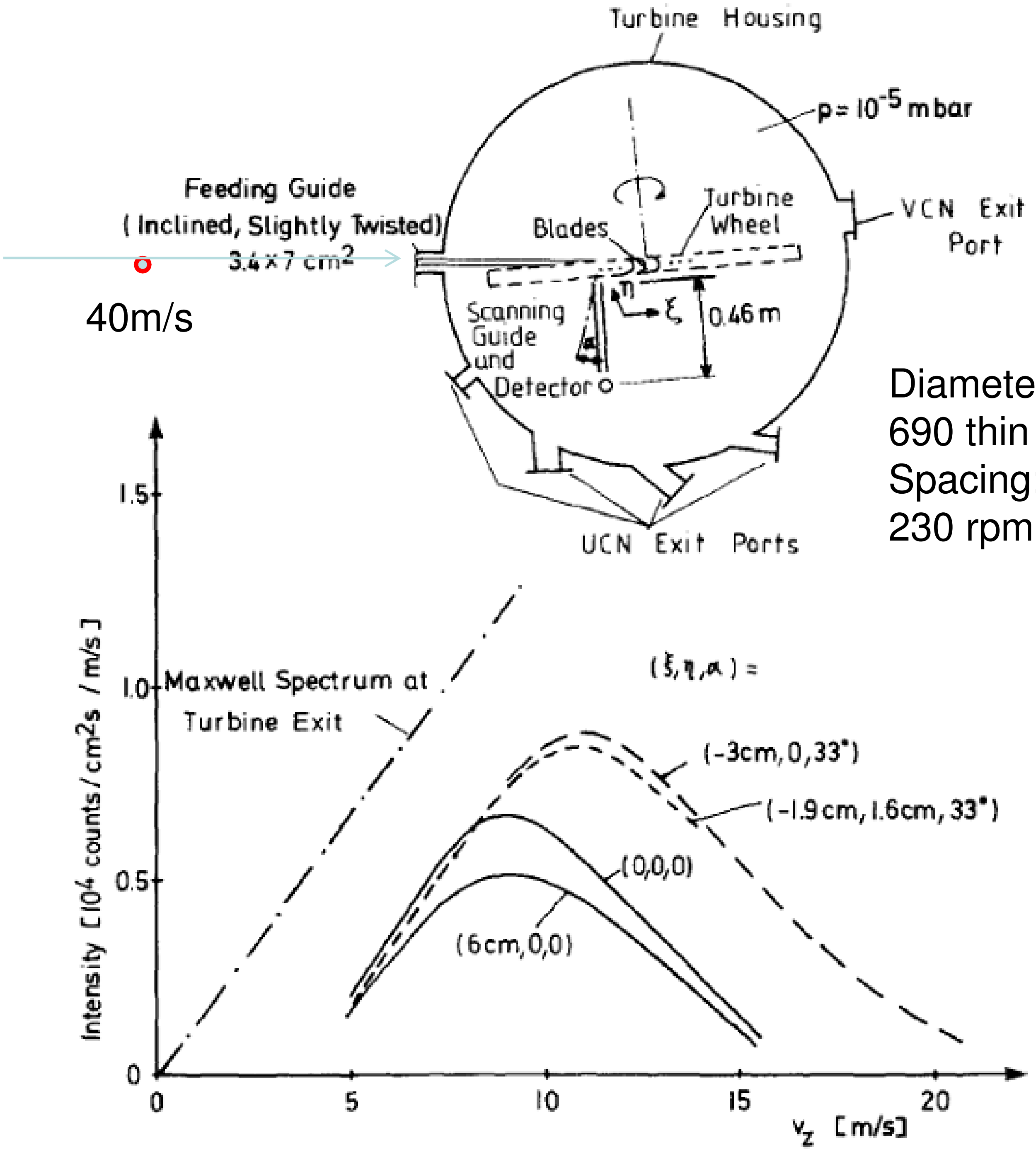


UCN yield as a function of source temperature (hydrogen)

$\Phi_{th} \sim 2 \times 10^{14}$ n cm^{-2} s^{-1}

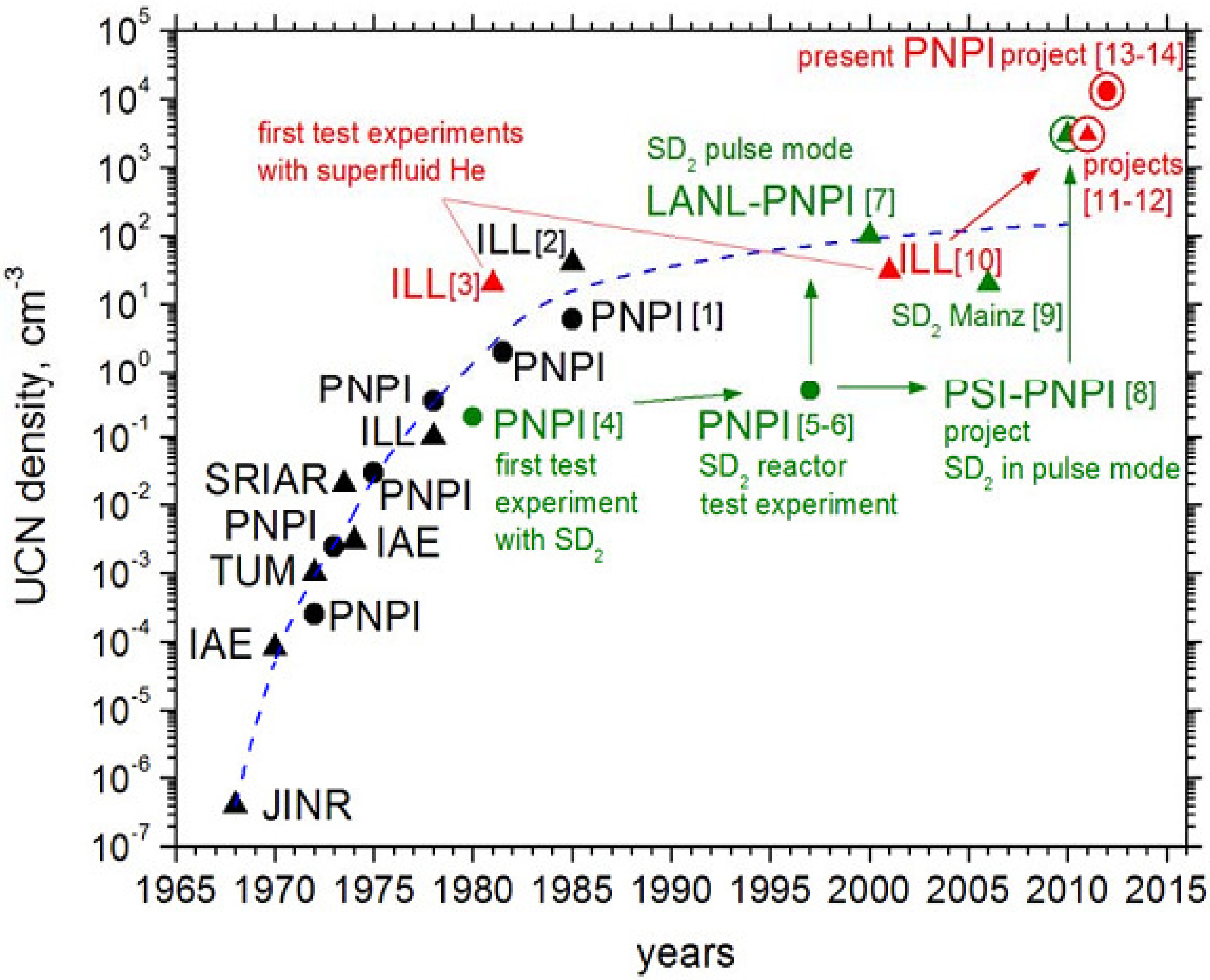
$\rho \sim 16$ cm^{-3}

Steyerl, 1975



Diameter: 1.7m
690 thin nickel curved blades
Spacing: 7.7mm
230 rpm

UCN Source Worldwide



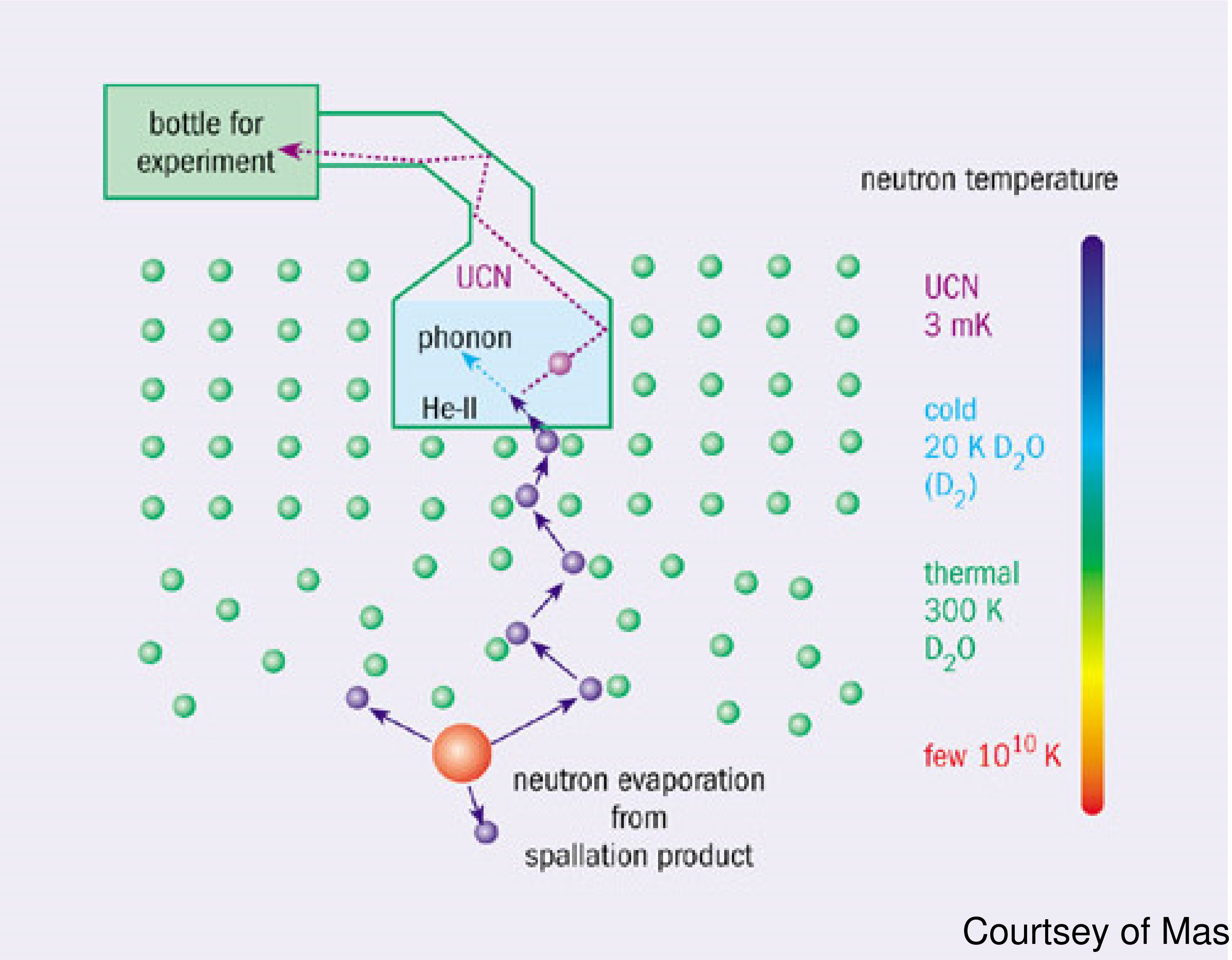
- Solid D2 based Source

LANL (existing)
PSI, TUM, Mainz, NCSU (in construction)
LENS (planned)

- Liquid Helium based Source

Osaka, ILL (prototype)
PNPI (in construction)
TRIUMF (proposed)

UCN Production: Neutron Cooling

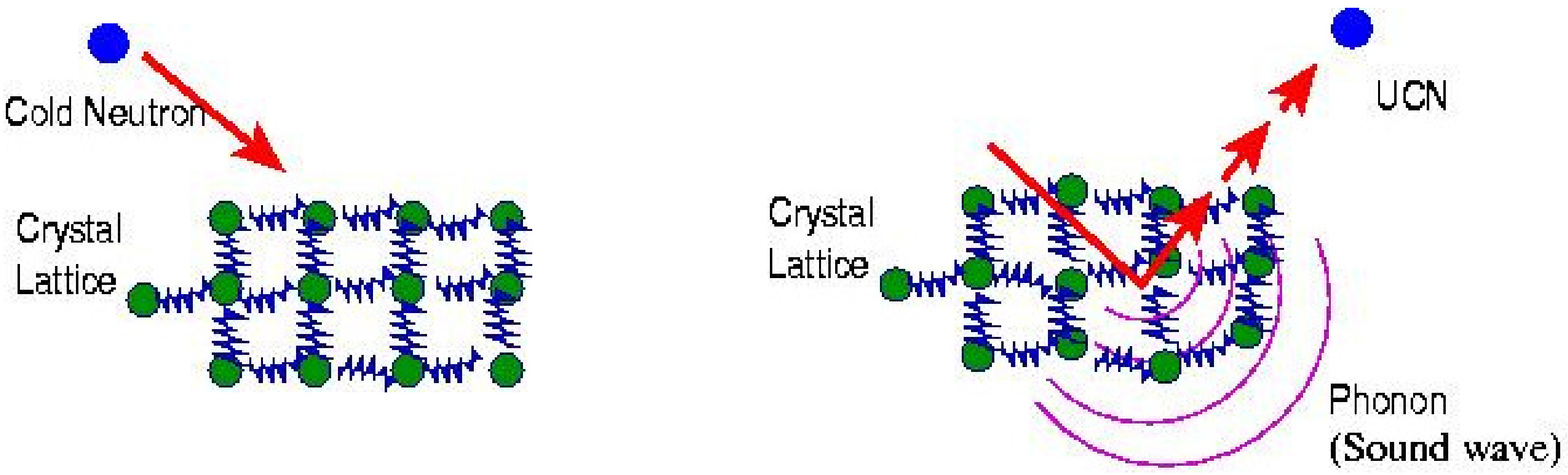


Courtsey of Masuda

Superthermal Process

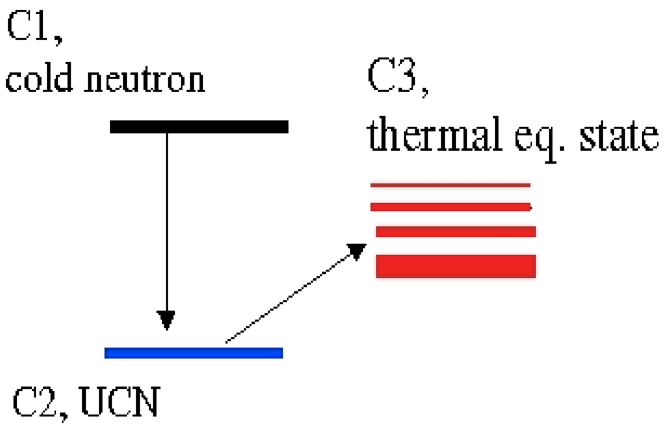
R. Golub and J. M. Pendlebury, Phys. Lett, A53, 133 (1975)

- 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.

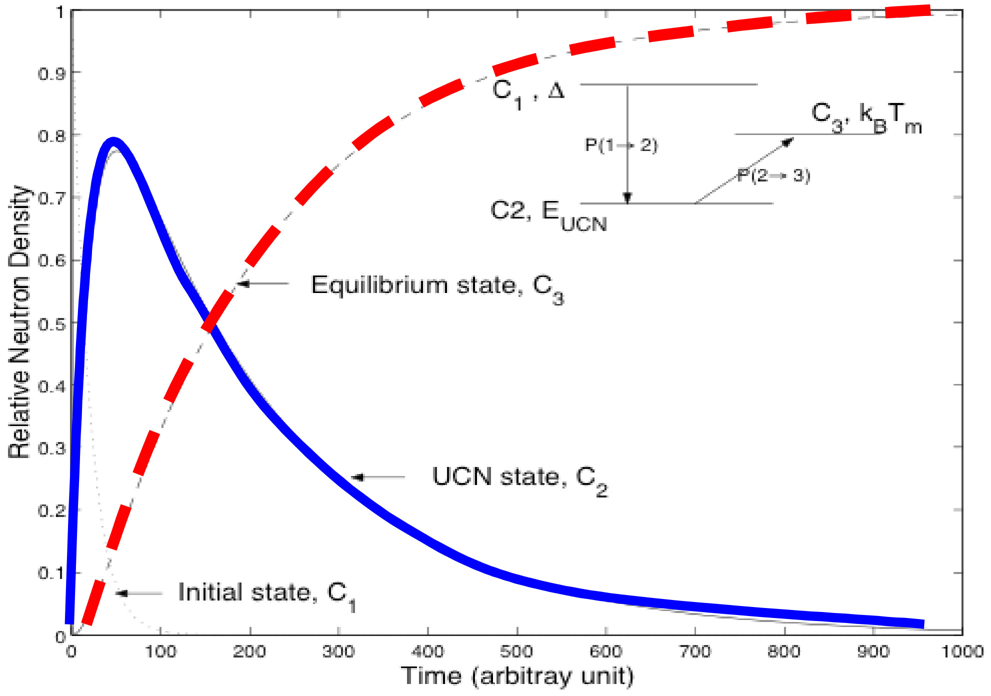
Dynamics of UCN Production --
Defeat thermal equilibrium



C1,
cold neutron

C3,
thermal eq. state

C2, UCN



- 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

Neutron Scattering in Condensed Matter

- Scattering Cross-section (First Born Approximation)

$$\frac{d^2\sigma}{d\Omega d\omega} = \frac{k'}{k}|\langle k'\lambda'|V(r,t)|k\lambda\rangle|^2\delta(\hbar\omega + \epsilon_\lambda - \epsilon_{\lambda'})$$

- Fermi (nuclear) Interaction in a lattice

$$V(r,t) = \sum_l b_l\delta(r - r_l)$$

- The Generalized Time Dependent Potential

$$V(r,t) = \underbrace{\bar{V}(r)}_{} + \underbrace{\delta V(r,t)}_{}$$

Static Average

Coherent Bragg scattering

Deviation from Average

Incoherent scattering (Isotope, spin fluctuation)

Inelastic scattering (time fluctuation)

diffusive scattering (defects of lattice)

Inelastic Coherent Neutron Scattering in Superfluid ^{4}He

- ^{4}He: σ_{coh} = 1.34 barn, and σ_{inc} = 0 barn
- Interaction depends only on spatial coordinate, r.

$$V(r,t) = \sum_l b_l^c \delta(r - r_l(t))$$

$$|\langle k'|V(r,t)|k\rangle|^2 = b^2 \sum_{l,l'} \langle e^{-ik\cdot r_l} e^{ik\cdot k'_l}\rangle$$

$$\frac{d^2\sigma}{d\Omega d\omega} = \frac{k'}{k}\frac{b^2}{2\pi\hbar}\int \; dt \;\; e^{-i\omega t} \sum_{l,l'} \underbrace{\langle e^{-ik\cdot r_l} e^{ik\cdot k'_l}\rangle}_{\Downarrow}$$

$$\{ \;\; 1 + \langle k\cdot u_l k\cdot u'_l(t)\rangle + O(k^4)\}$$

Using a, a^+ algebra for simple harmonic oscillators:

$$\frac{d^2\sigma}{d\Omega d\omega} = \frac{\sigma_c}{4\pi} \frac{k'}{k} \frac{(2\pi)^3}{v} \frac{1}{2M} \sum_{j,q} e^{-2W(k)} \frac{|k \cdot \sigma^j(q)|^2}{\omega_j(q)}$$

$$\Big[\; n_j(q)\delta(\omega + \omega_j(q))\delta(k+q) \leftarrow \text{upscattering}$$

$$+ \; (1 + n_j(q))\delta(\omega - \omega_j(q))\delta(k-q)\Big] \leftarrow \text{downscattering}$$

- Upscattering rate scales linearly n, the number of phonons presents.

$$n(\epsilon) = \frac{1}{e^{\epsilon/kT} - 1}$$

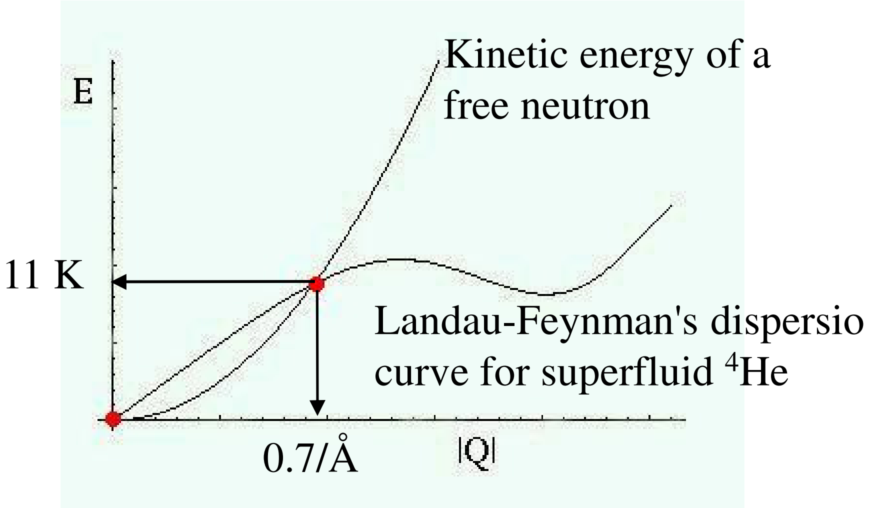
- Downscattering rate scales with the density of states, $Z(\epsilon)$, of phonon.

$$\sum_q \simeq \frac{(2\pi)^3}{V} \int d\epsilon Z(\epsilon)$$

- Large intrinsic cross-section, σ_c.
- Light mass.

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

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

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

Superthermal gain

S(Q,ω) for liquid He

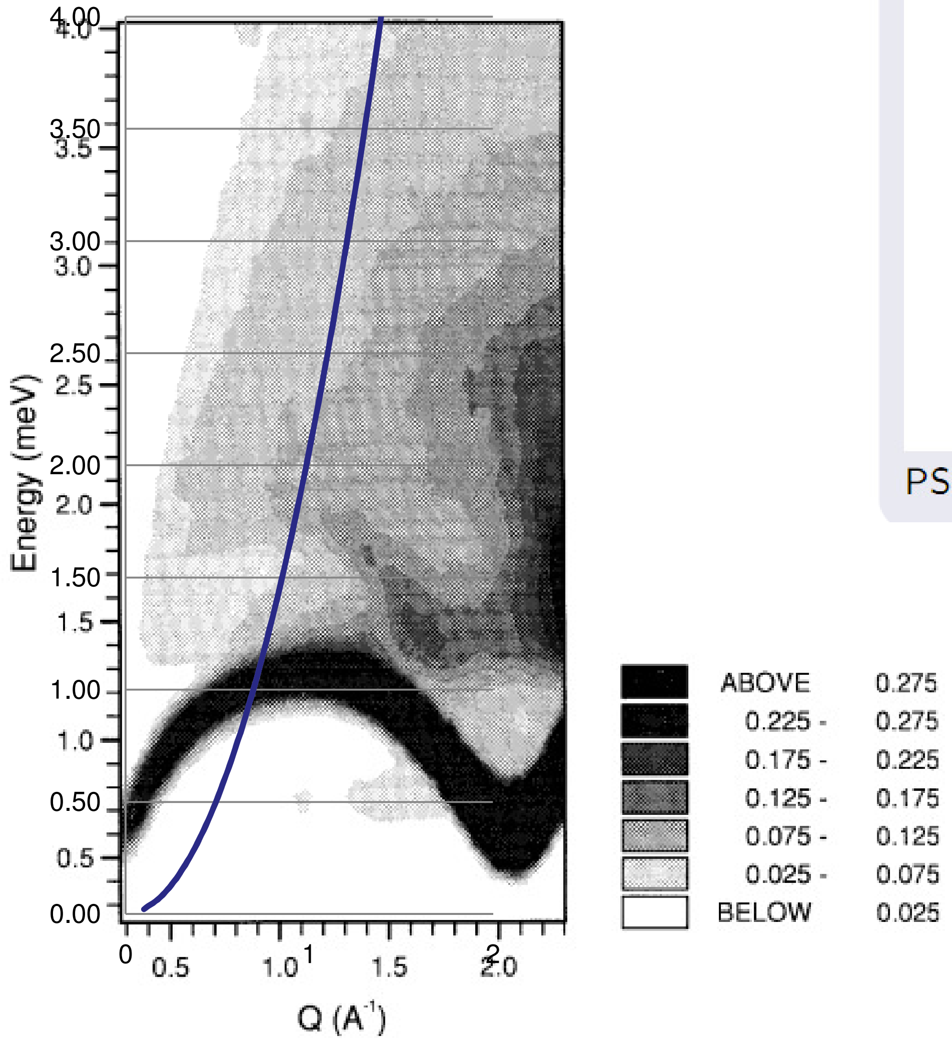
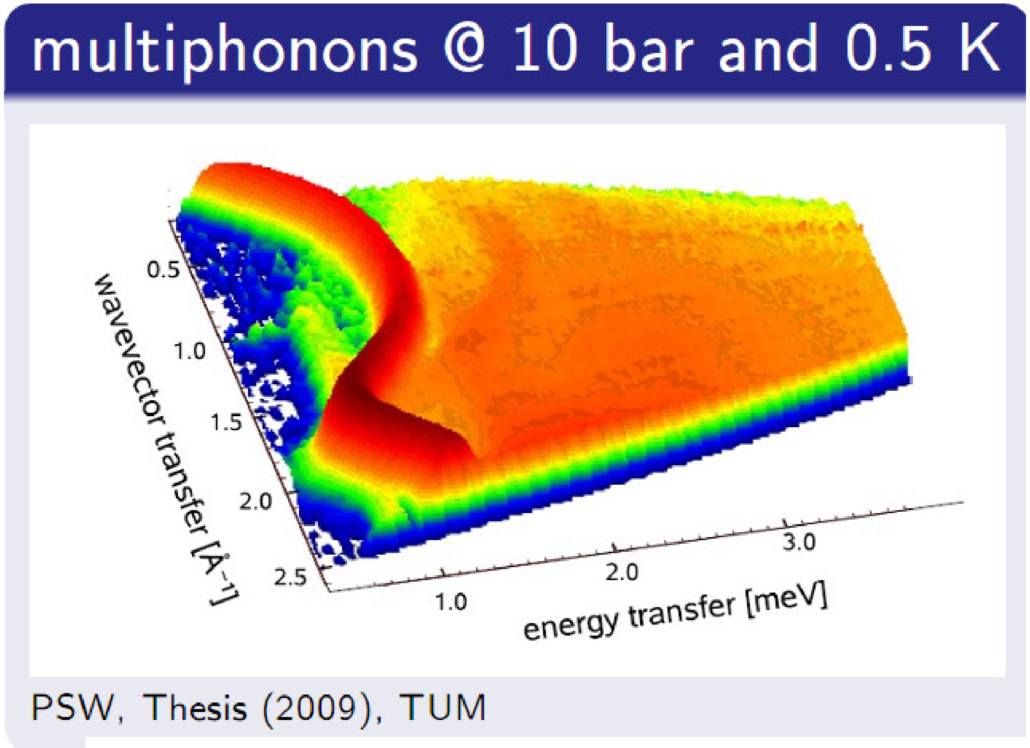


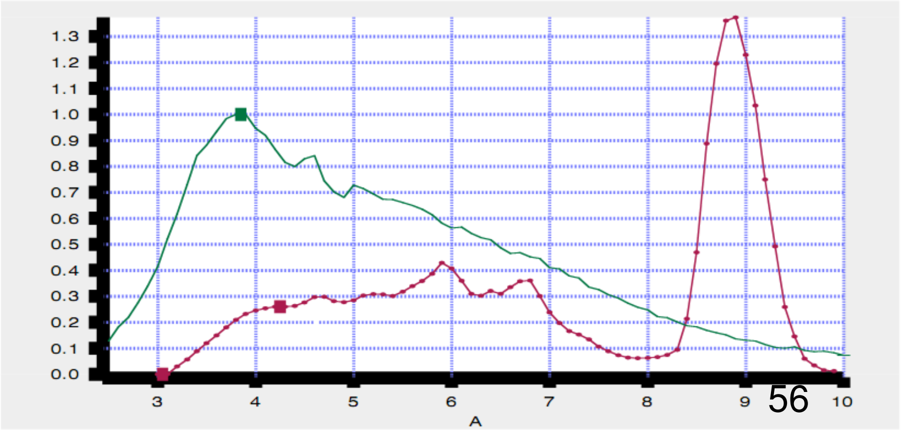
Fig. 1. Contour plot of the dynamic structure factor (units, meV^{-1}) of superfluid ^{4}He at 0.5 K, $P = 20$ bars. The sharp phonon–roton excitations have been removed revealing the intensity of the multiphonon excitations. The feature observed at $Q \sim 1.6$ Å^{-1} and $E = 0.75$ meV is due to multiple scattering involving single rotons and elastic scattering from the Al cell.



multiphonons @ 10 bar and 0.5 K

PSW, Thesis (2009), TUM

Multi-Phonon Processes



Superfluid ^{4}He – UCN loss

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

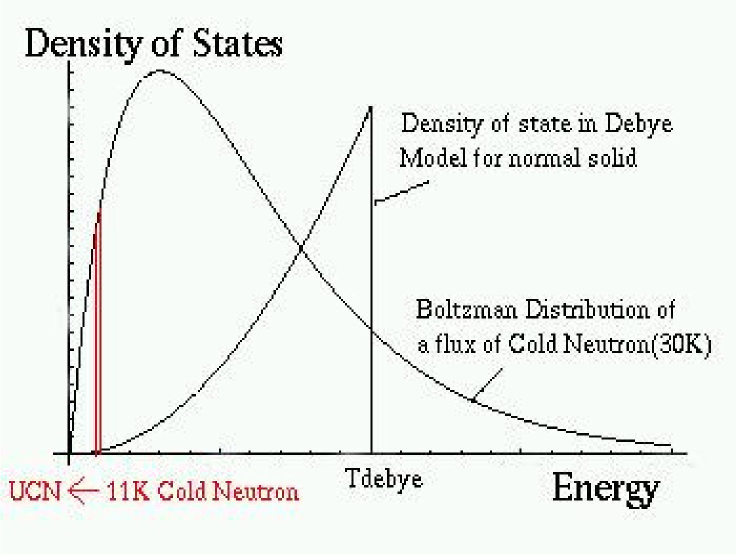
Isotop	σ_{coh}	σ_{inc}	σ_a	σ_s/σ_a	*purity*	*Debye T*
^{2}D	5.59	2.04	0.000519	1.47×10^4	99.82	110
^{4}He	1.13	0	0	∞		20
^{15}N	5.23	0.0005	0.000024	2.1×10^5	99.9999	80
^{16}O	4.23	0	0.00010	2.2×10^4	99.95	104
^{208}Pb	11.7	0	0.00049	2.38×10^4	99.93	105

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.

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

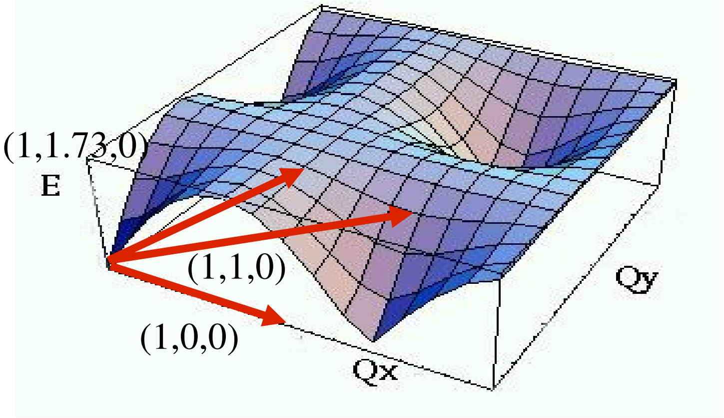
➔ All the Cold Neutron with energy smaller than the Debye T could become UCN through incoherent phonon creation.

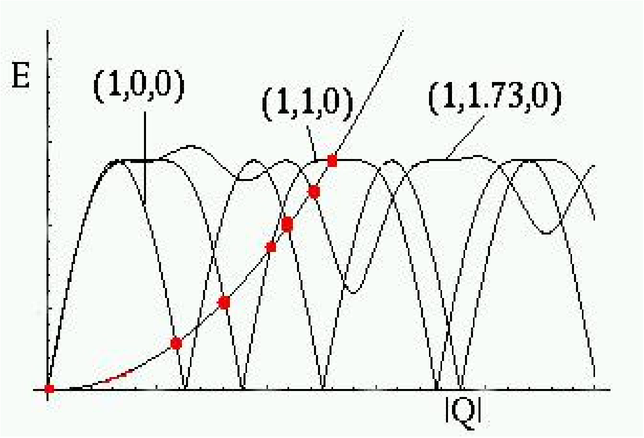


Solid D2 – UCN production (II)

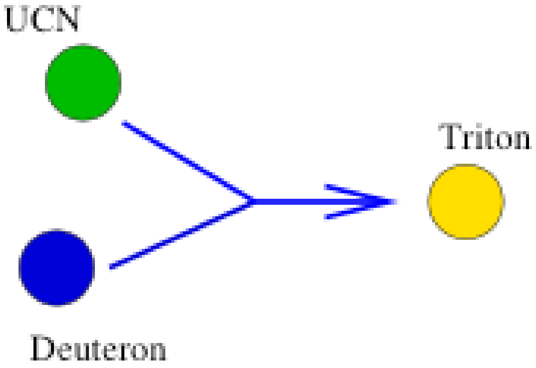
- Coherent contribution (σ_{coh}= **5.59 barn**)
  - Momentum and energy conservations are still strictly hold.
  - The anisotropic dispersion relation broadens the range of conditions for single phonon creation process.

  ➔ In a cold neutron flux with a continuous spectrum, more neutrons could participate in the UCN production.



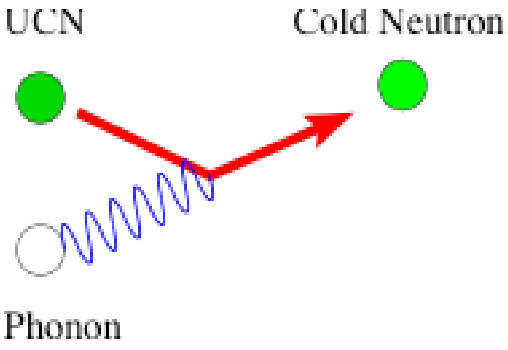


Solid Deuterium - UCN Loss



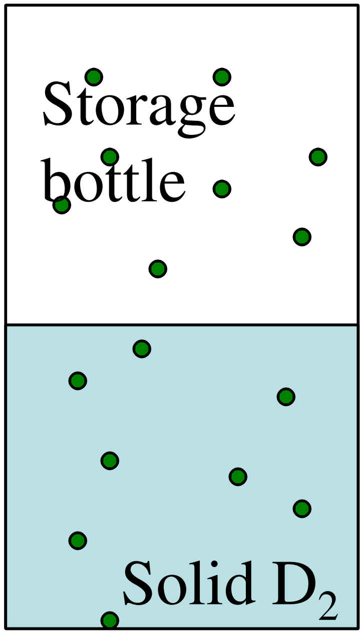
Nuclear absorption by S-D_2

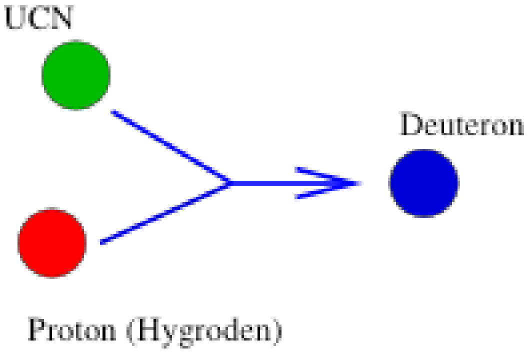
τ ~ 150 msec



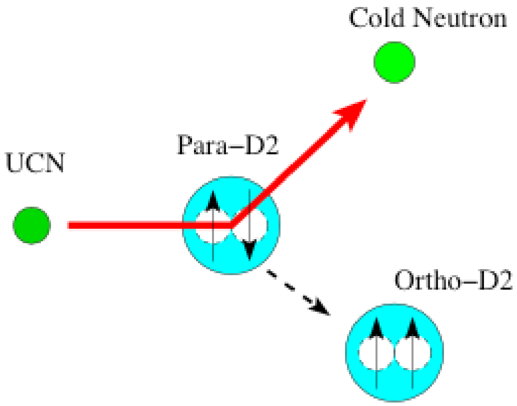
UCN upscattering by phonons

τ ~ 150 msec at T = 5K





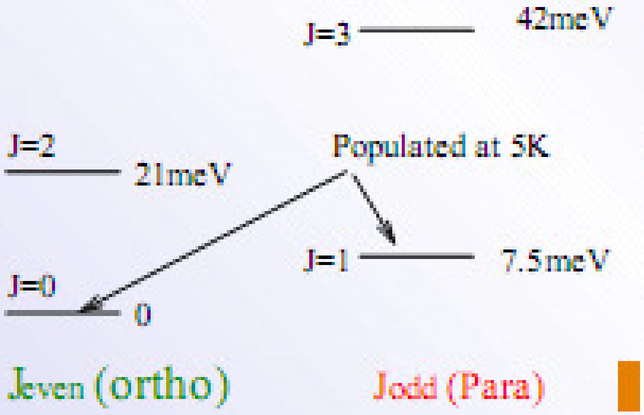
Nuclear absorption by Hydrogen Impurities, **τ ~ 150 msec/0.2% of H**



UCN upscattering by para-D_2

τ ~ 150 msec/1% of para-D_2

Para-D_2 Upscattering



Diatomic Molecule:

$$V(r)=\sum_i \underbrace{b\delta(r-R_i^1)+b\delta(r-R_i^2)}_{\Downarrow}$$

(Rotation)×(Translation)

(Rotation) around the C.M.

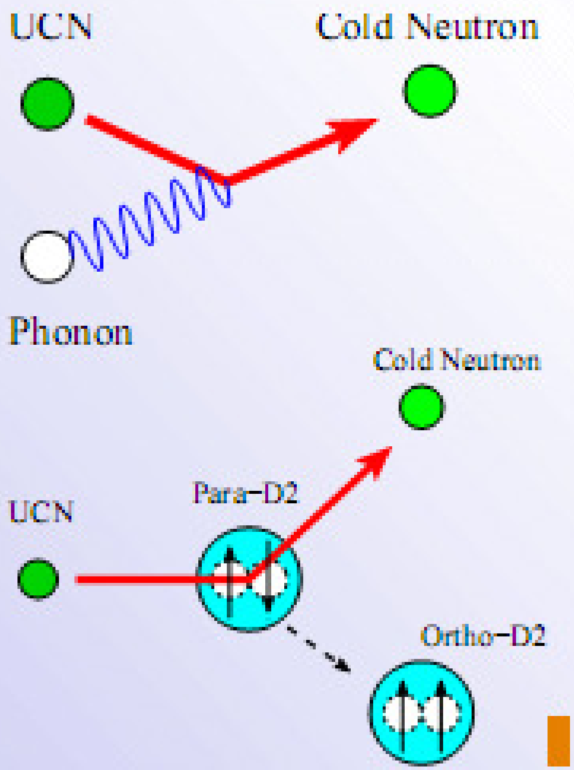
$\sum_{l=|J'-J|}^{J'+J} S_{JJ'}(2J'+1)|A_{0l}|^2C^2(JJ'l;00)e^{i(\epsilon_J-\epsilon_J)t/\hbar}$

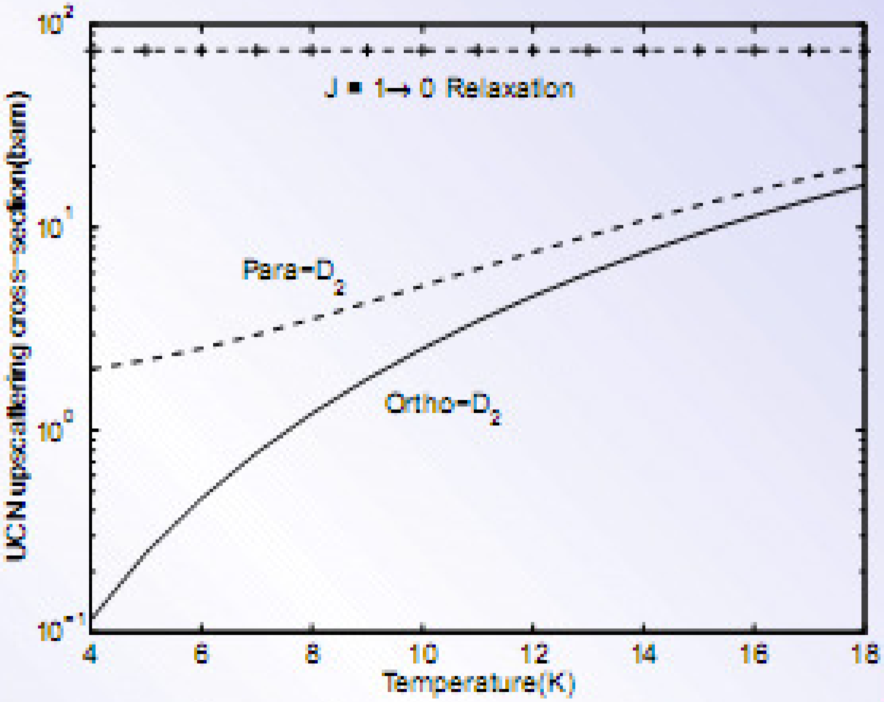
(Translation) of the C.M.

$\underbrace{\delta(\omega)}+\langle k\cdot uk\cdot u'(t)\rangle+O(k^4)$

Para-D_2 upscattering (no phonon coupling)

Para Upscattering Time

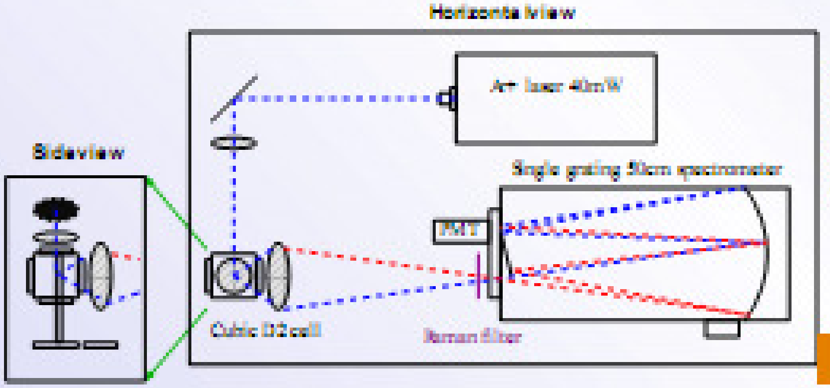


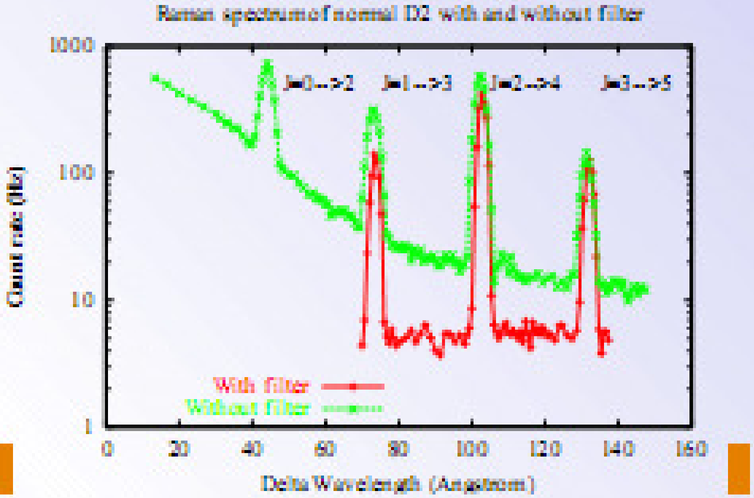


τ_{para} = 1.5 ms for pure para-D$_2$

τ_{para} = 5 ms for normal para-D$_2$ (33% para)

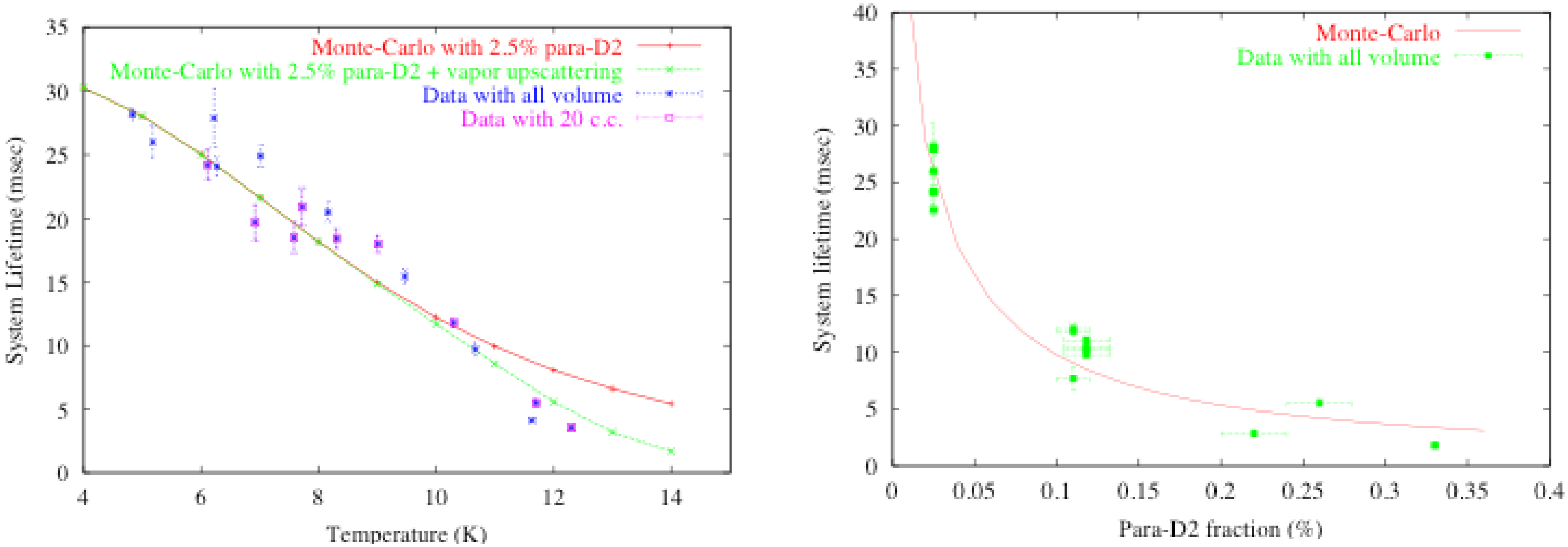
Monitor the Para-D_2 Content





UCN lifetime in S-D_2

LANL UCN prototype source (2000)

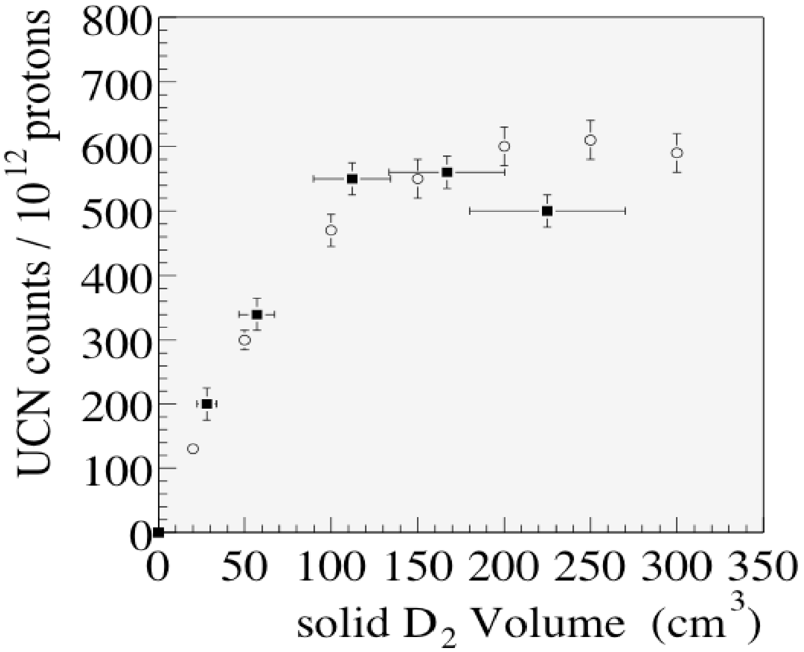


C. Morris *et al.*, Phy. Rev. Lett. **89**, 272501 (2002)

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

LANL UCN prototype source (2000)

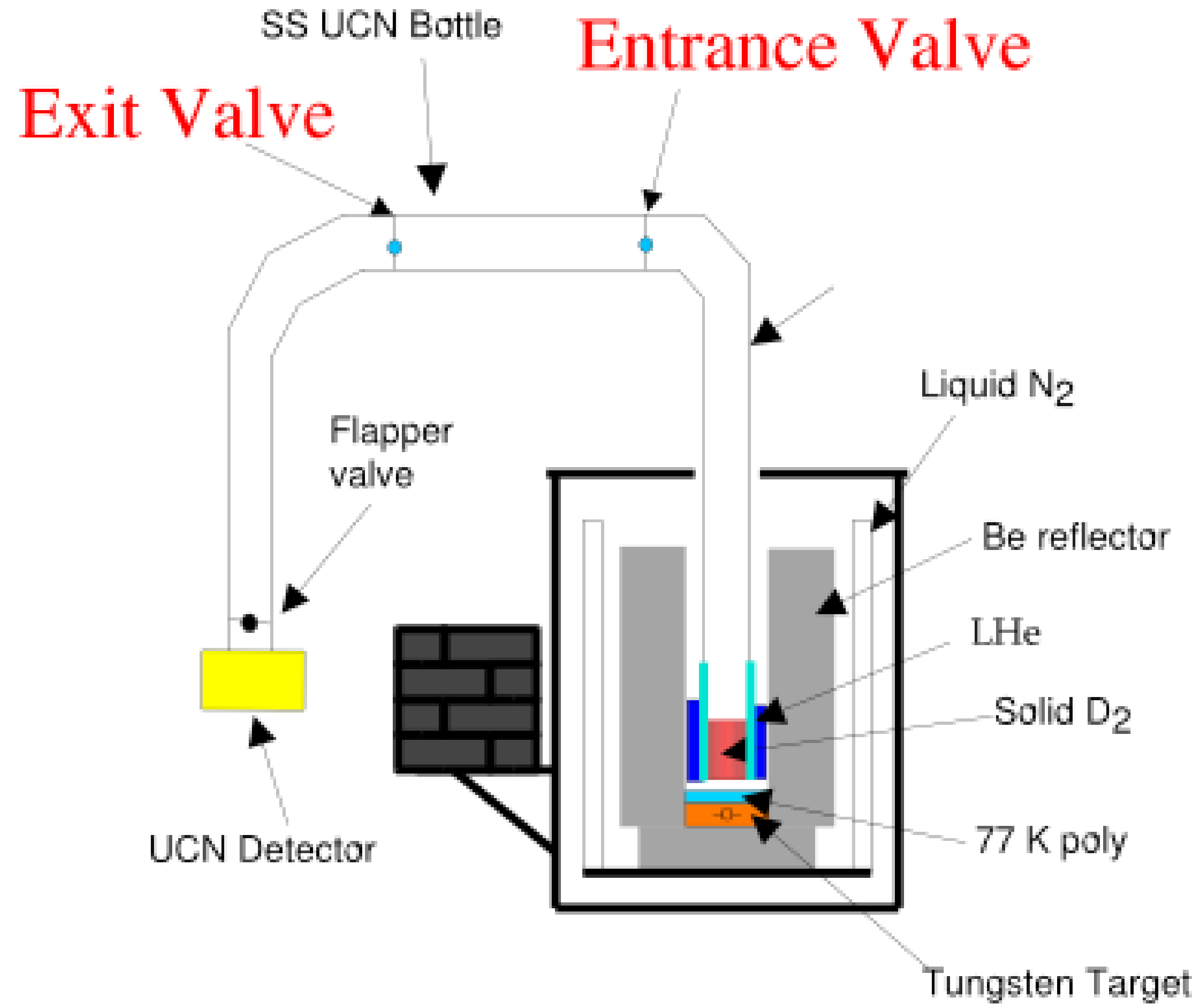
Volume Scan



- UCN yield saturates above 200 c.c ⇒ mean free path = 8 cm Resulted from UCN incoherent elastic scattering (random walk).

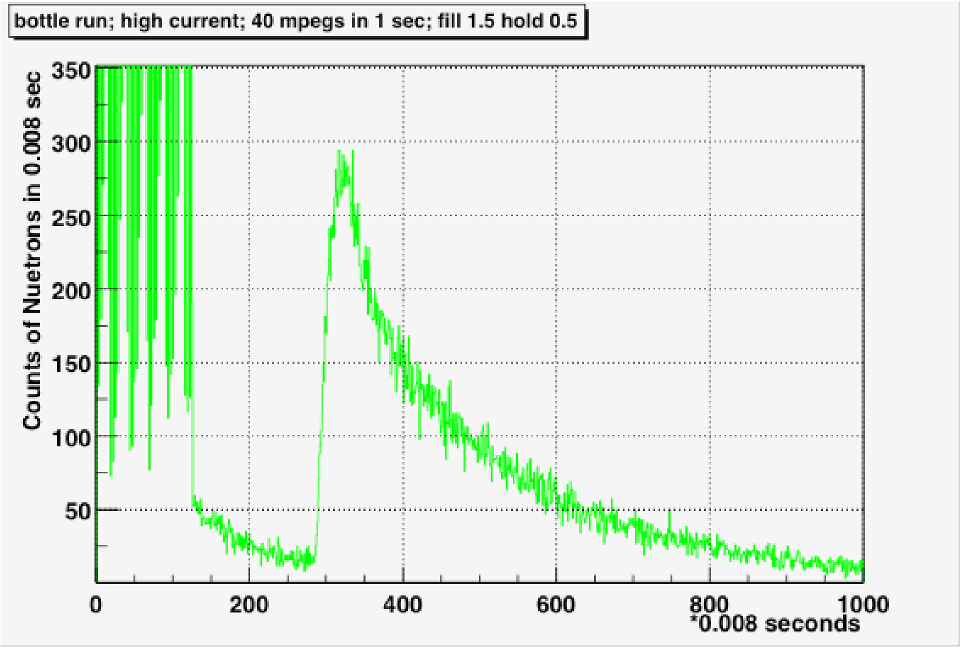
UCN Production Measurement -- Bottle Technique

LANL UCN prototype source

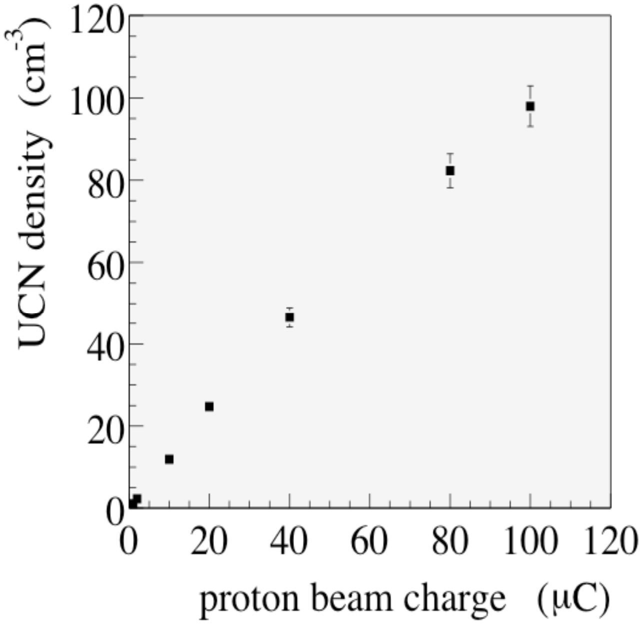


C. Morris *et al.*, Phy. Rev. Lett. 89, 272501 (2002)

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.

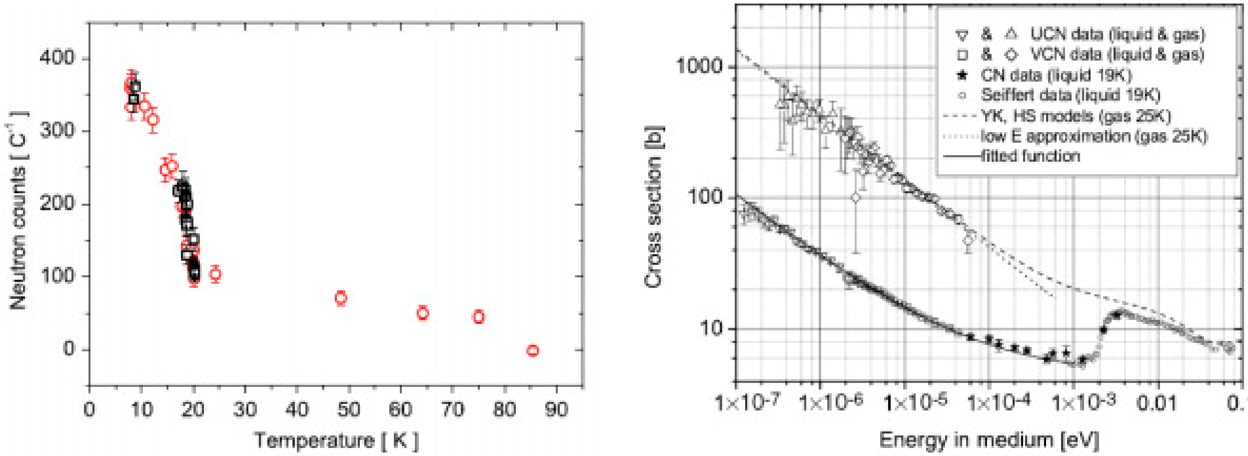
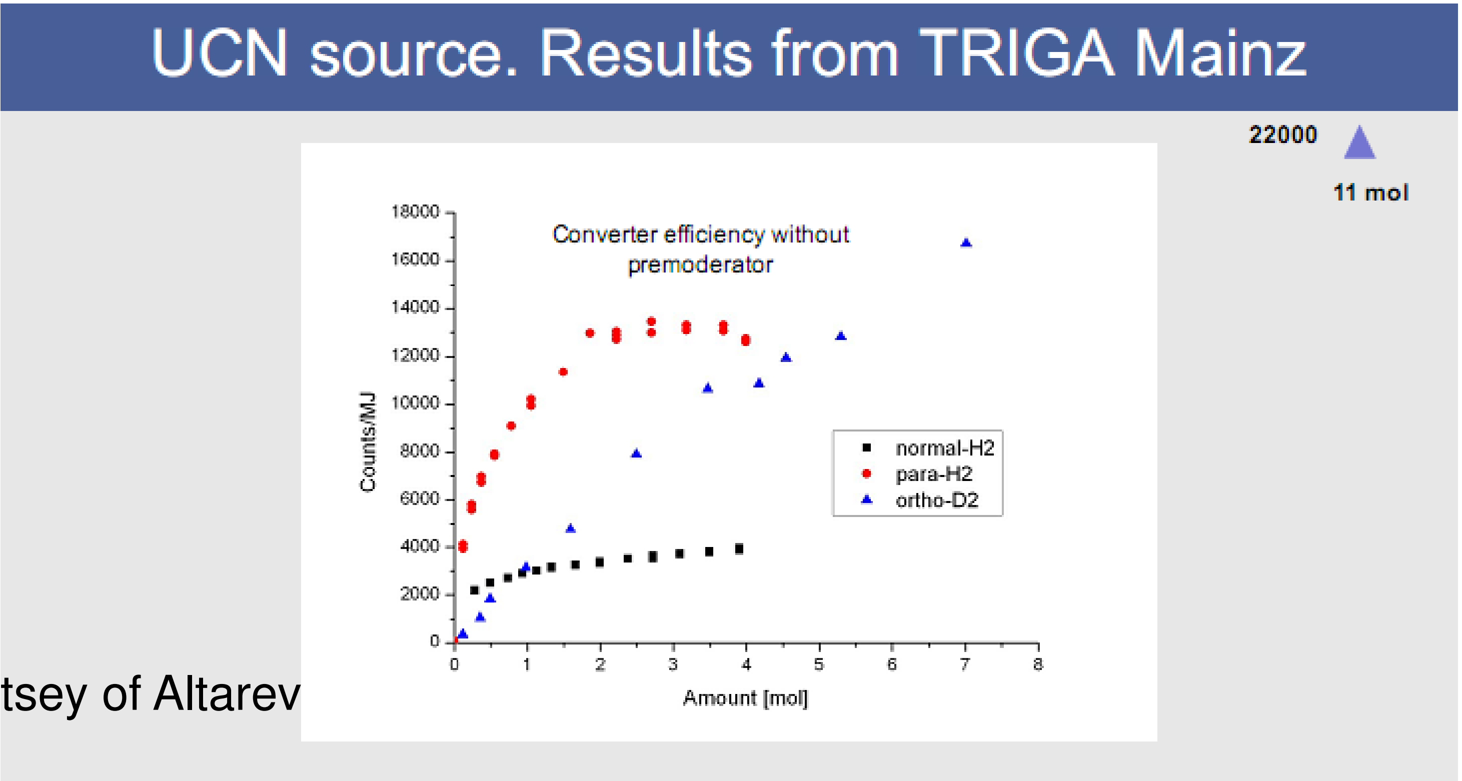


Fig. 1: On the left plot is the UCN production in solid deuterium as a function of the temperature of the deuterium UCN converter. [Atchi05-2]. On the right plot is the total cross-section of slow neutrons scattered by gaseous and liquid deuterium. [Atchi05]

PSI
Atchison et al. 2005



UCN source. Results from TRIGA Mainz

Courtsey of Altarev

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

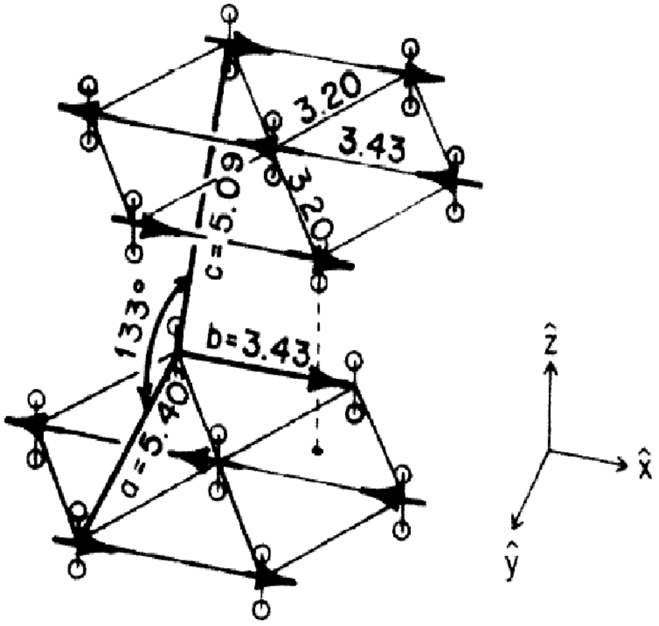
Too Heavy !

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

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

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

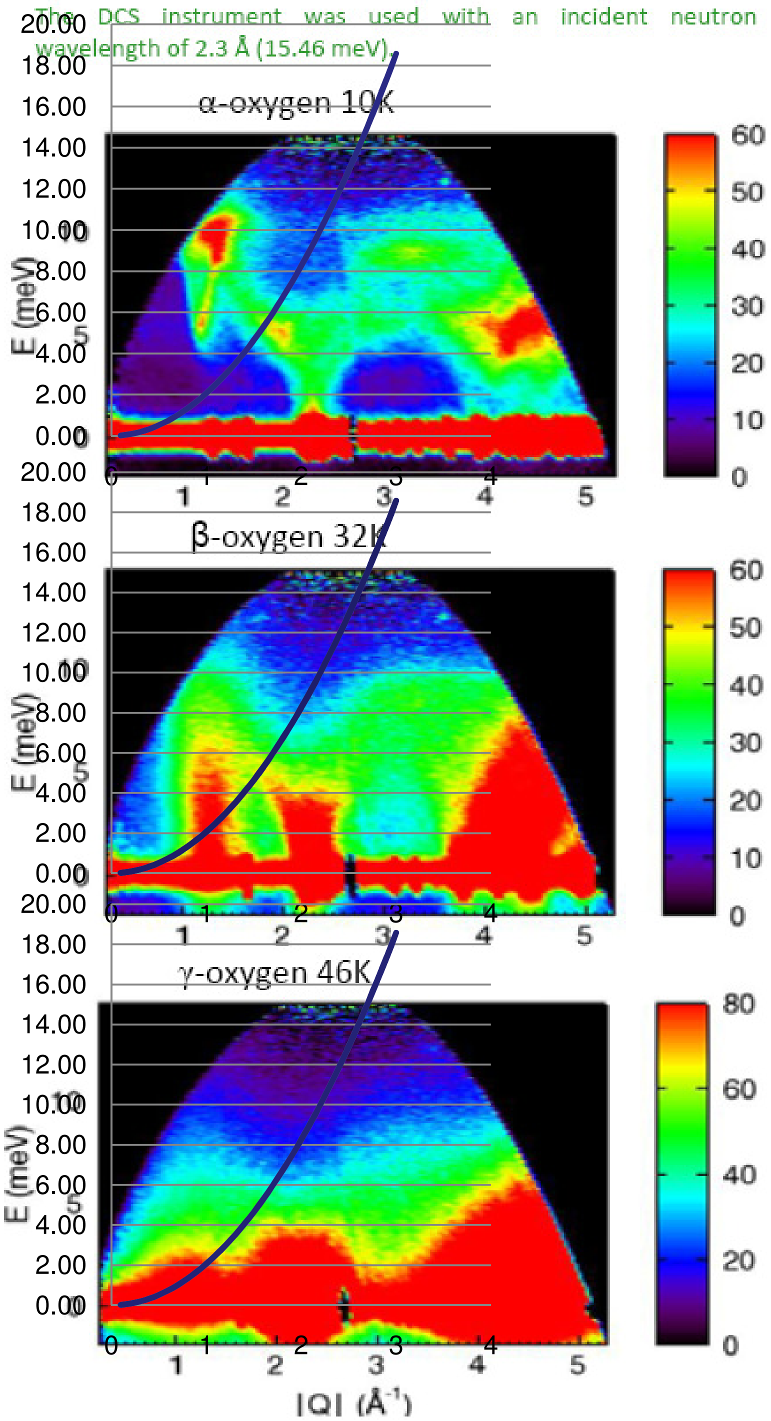
(Spin)×(Translation)

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

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

(1+magnon)×(1+phonon)

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

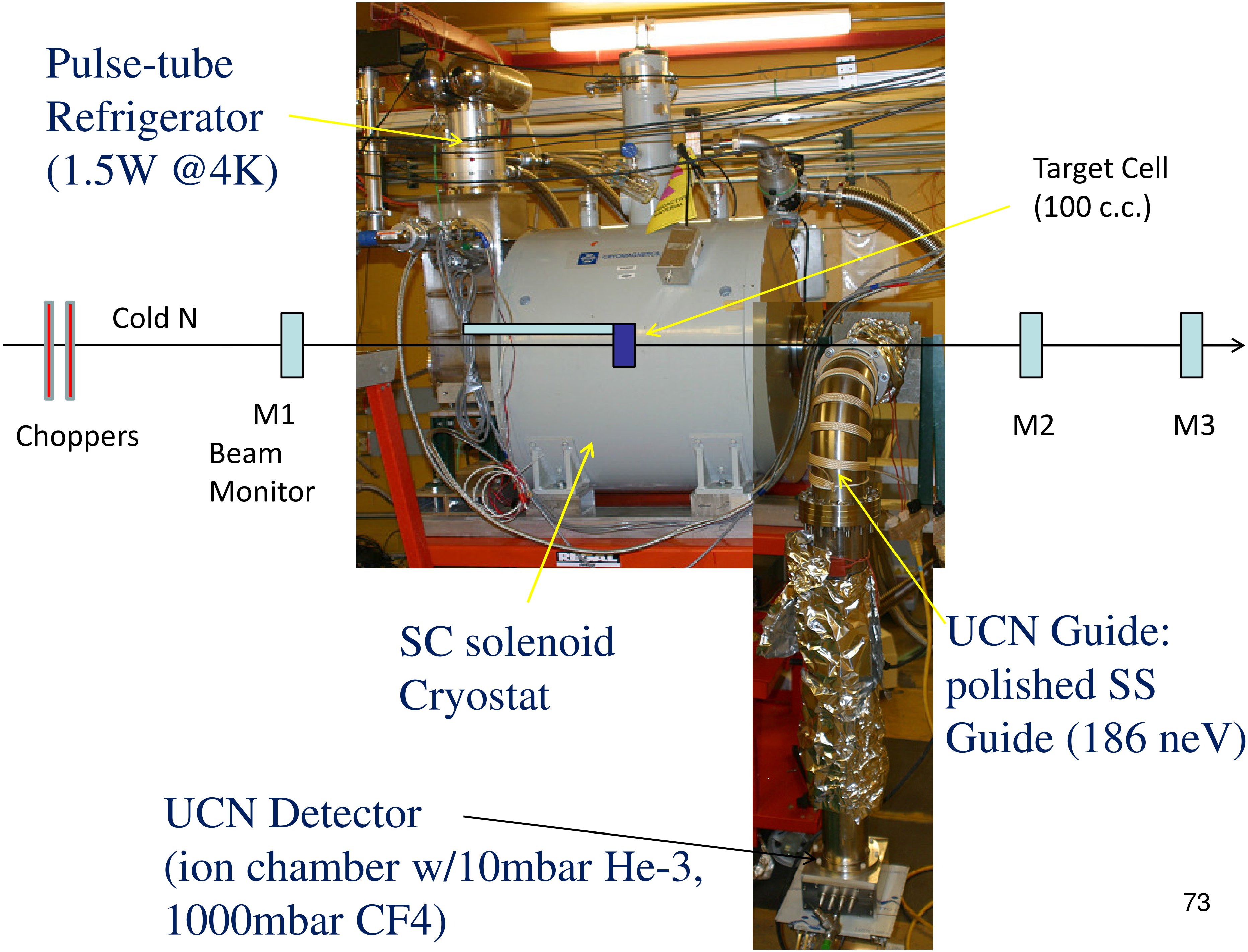


The DCS instrument was used with an incident neutron wavelength of 2.3 Å (15.46 meV).

Updated S(Q,ω)

- More detailed data taken at ISIS independently confirms these results
- Origins of the “soft” modes, precursors to the long-range AF order, in beta phase needs explanations.

D. Kilburn, P.E. Sokol, C. Brown, 2008
(DCS at NIST)



Pulse-tube Refrigerator (1.5W @4K)

Target Cell (100 c.c.)

Cold N

Choppers

M1 Beam Monitor

M2

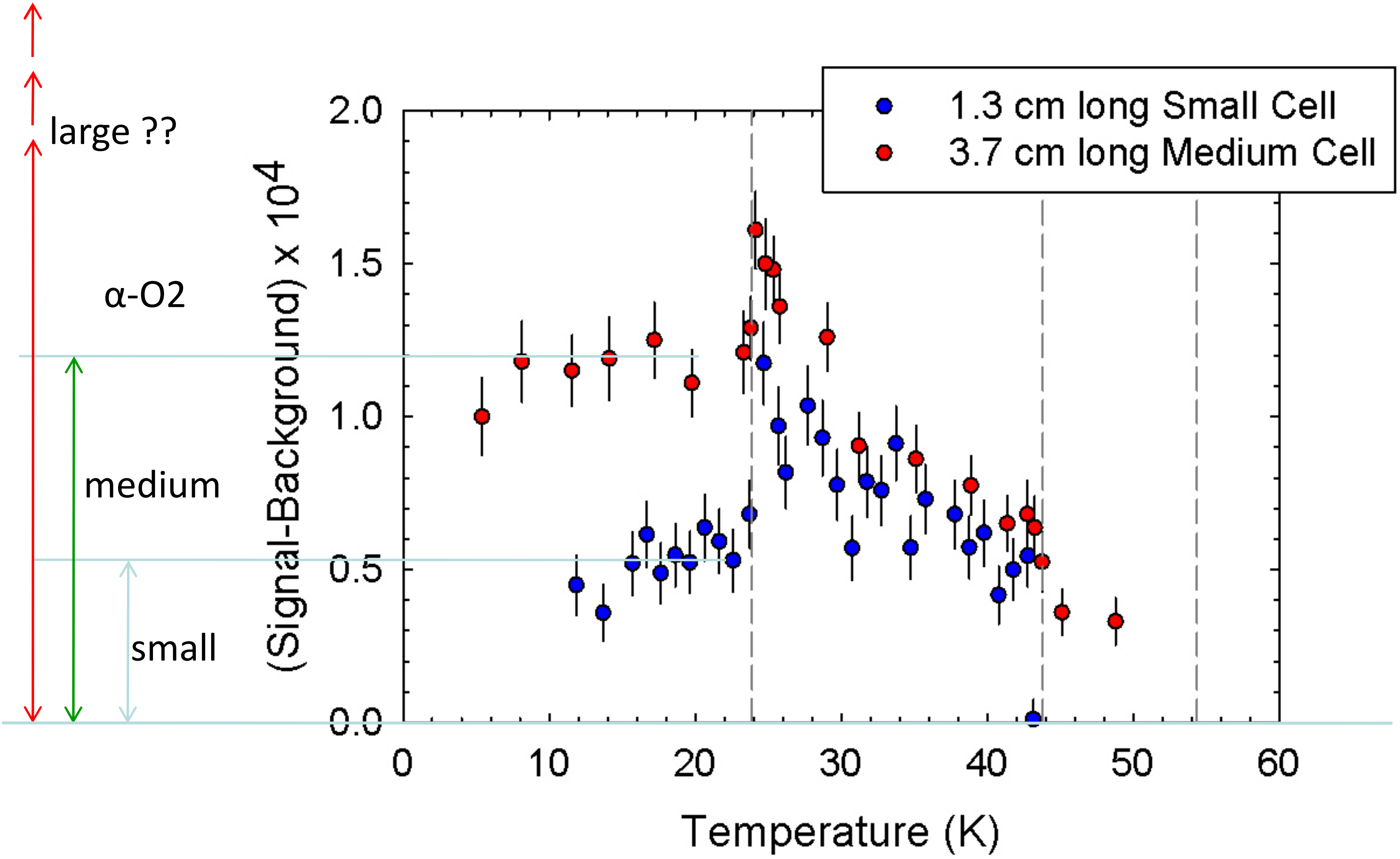
M3

SC solenoid Cryostat

UCN Guide: polished SS Guide (186 neV)

UCN Detector (ion chamber w/10mbar He-3, 1000mbar CF4)

UCN Production in S-O_2



large ??

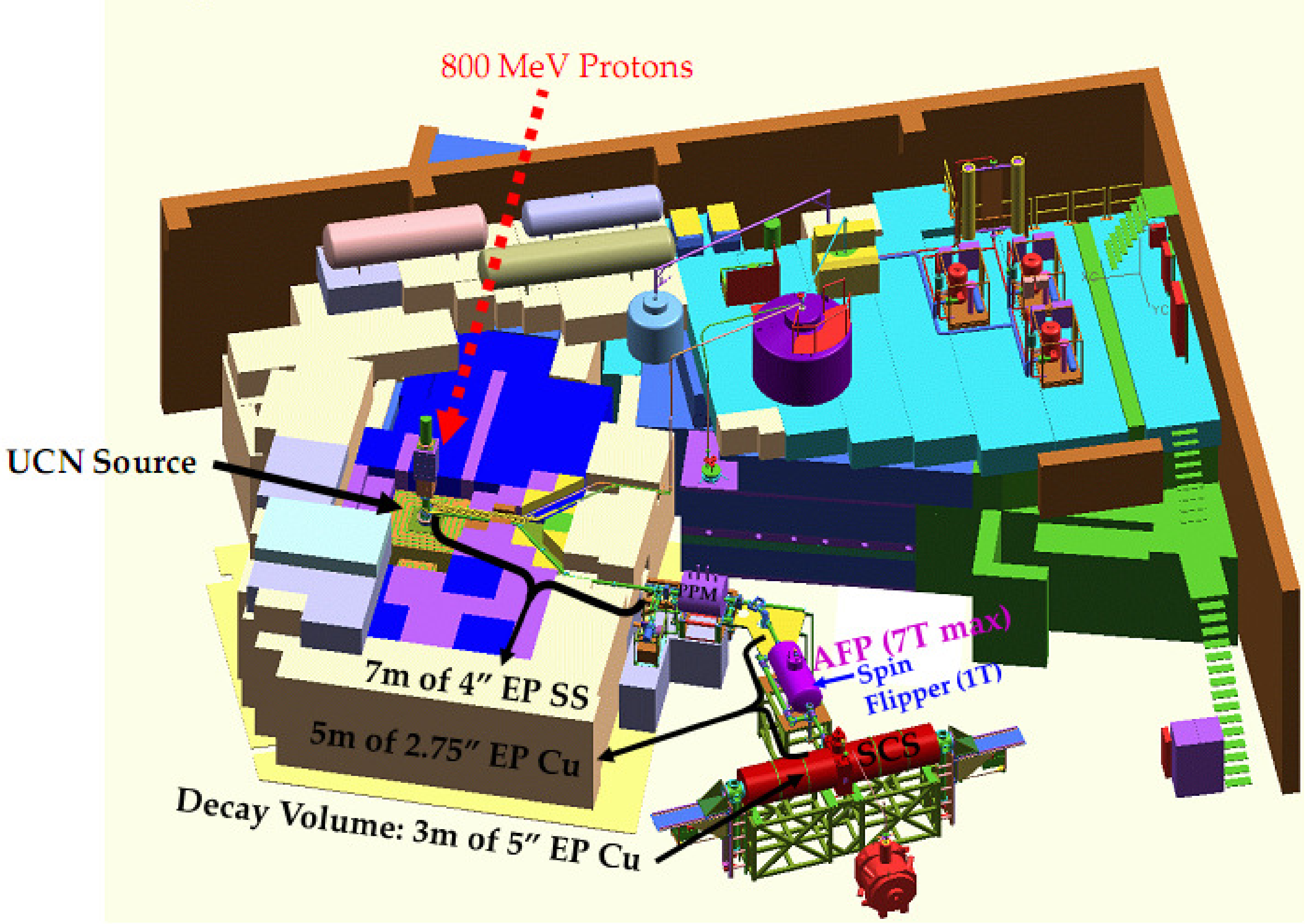
α-O2

medium

small

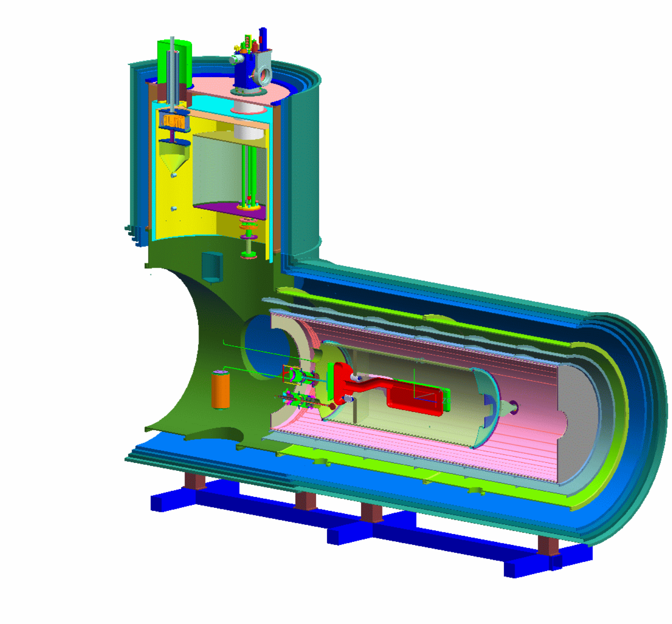
Los Alamos UCN Source

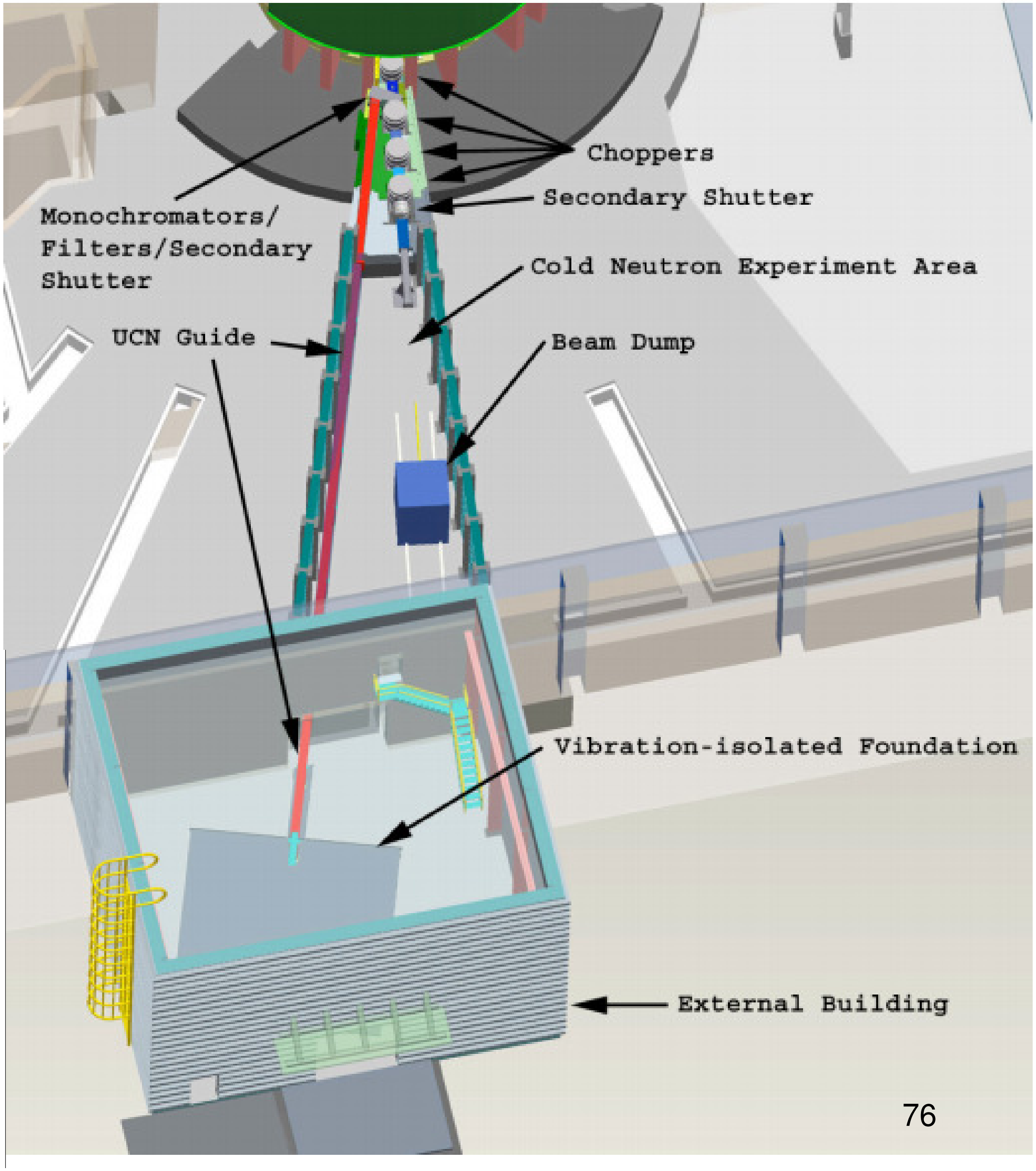
Measuring A with UCN: UCNA



SNS FNPB

SNS nEDM

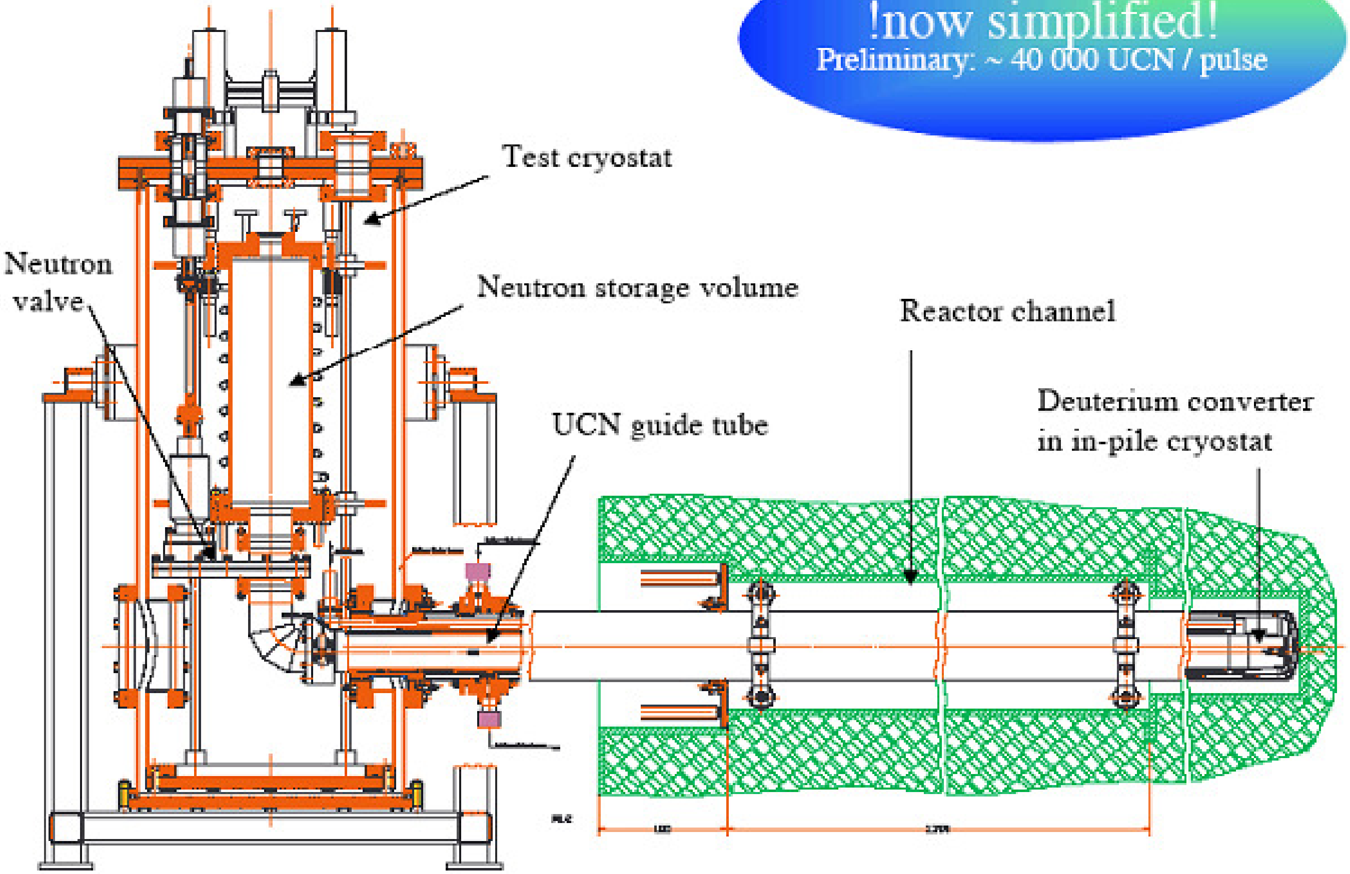




The TRIGA Mainz setup

!now simplified!

Preliminary: ~ 40 000 UCN / pulse



pulsed neutrons

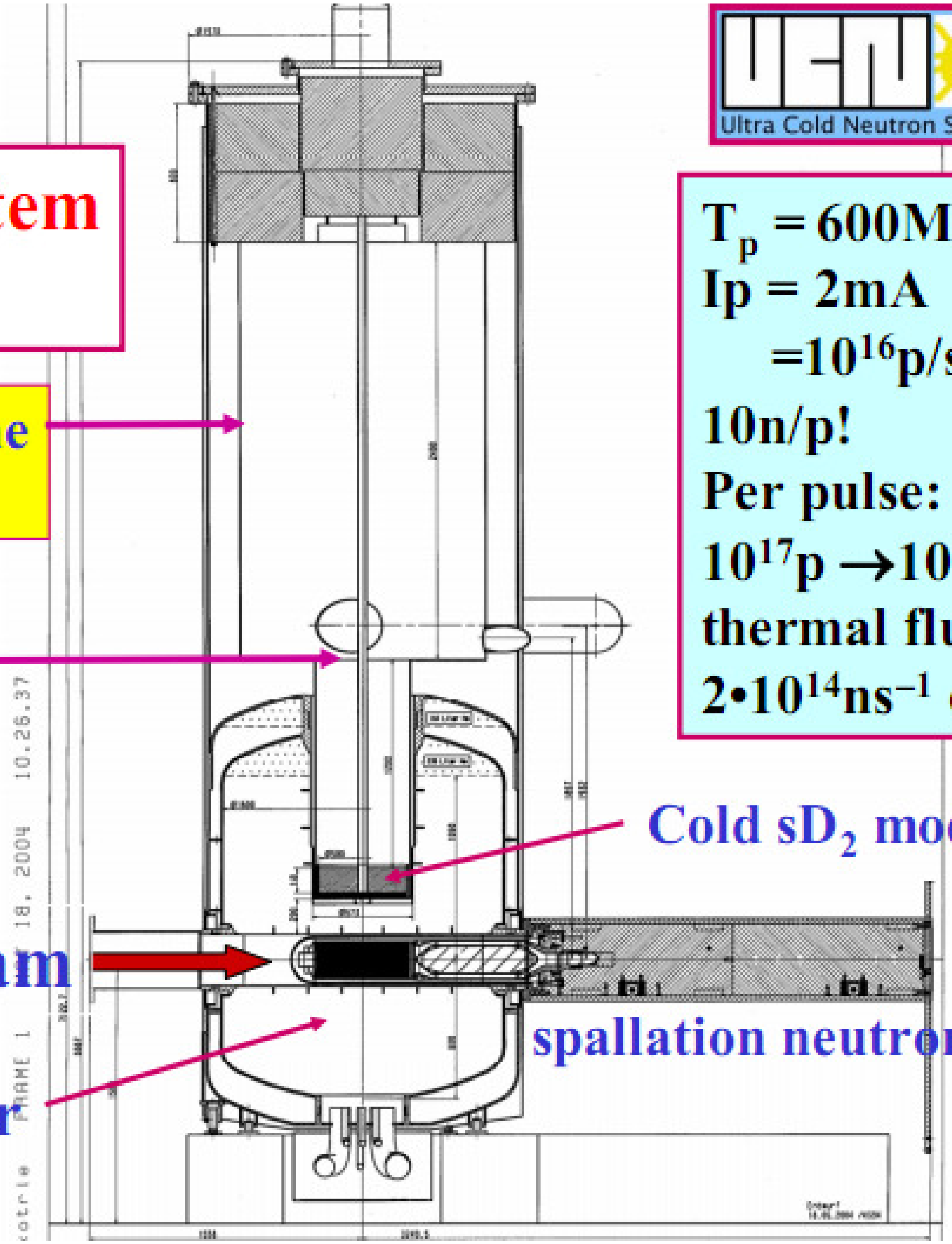
PAUL-SCHERRER-INSTITUT

PSI

UCN Tank System (~5m high!)

UCN

Ultra Cold Neutron Source



UCN storage volume $2m^3$

UCN shutter

p beam

D_2O moderator

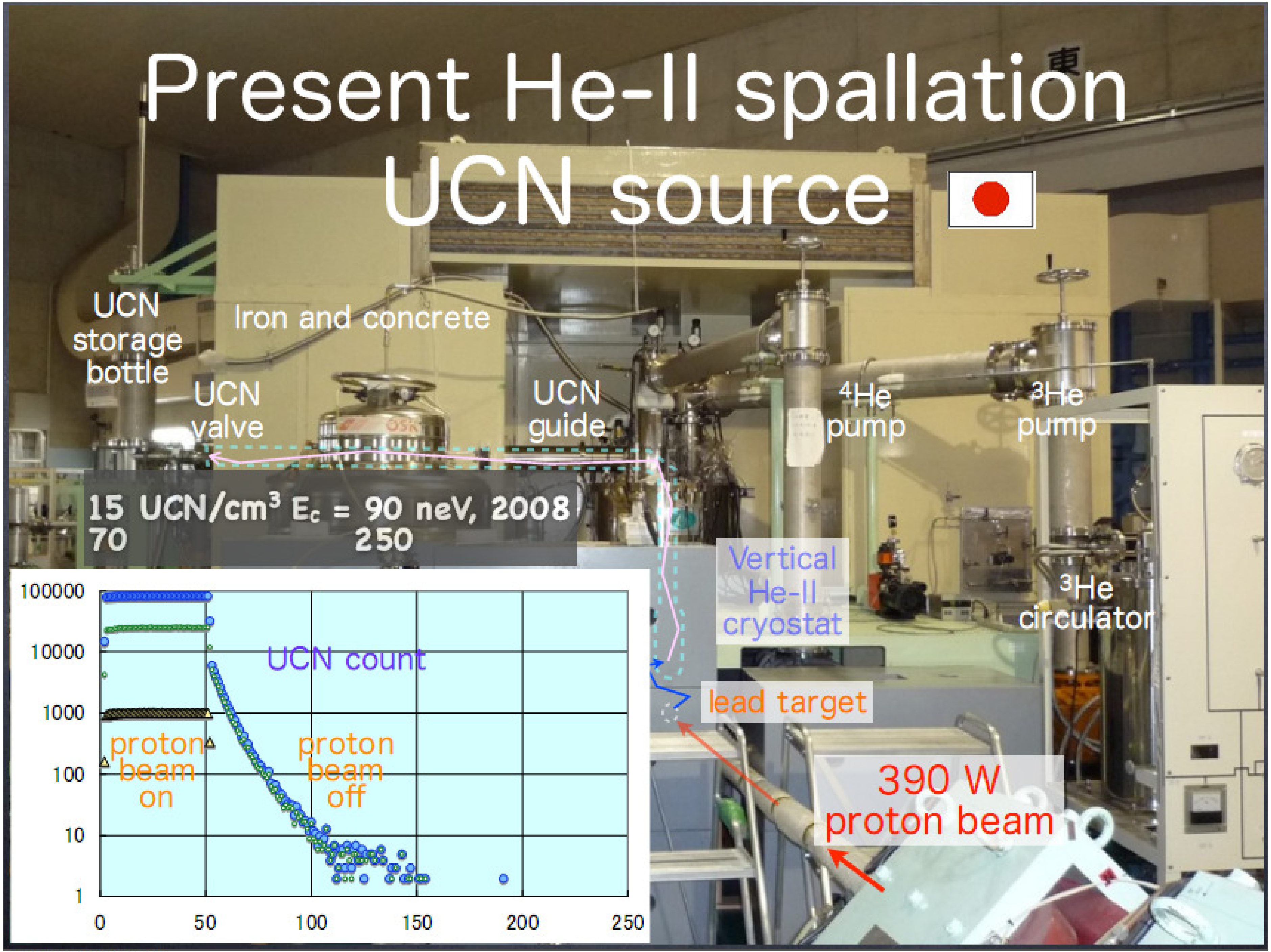
τ~6ms, s~12m

Cold sD_2 moderator

spallation neutron target

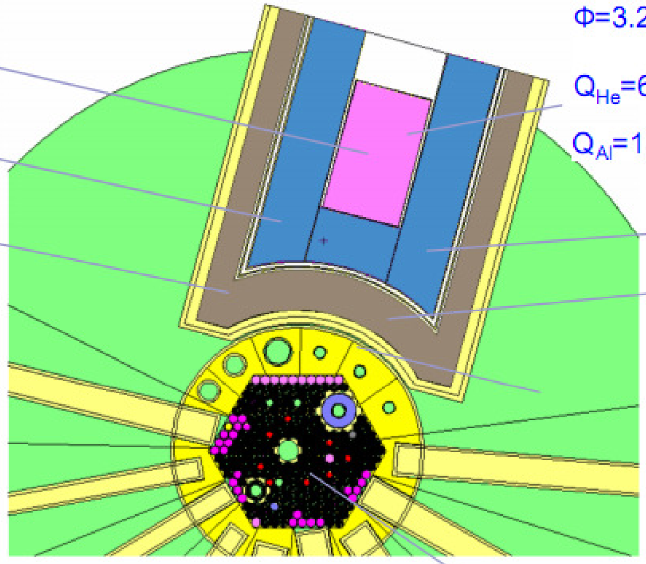
$T_p = 600MeV$
$I_p = 2mA$
$=10^{16} p/s$
10n/p!
Per pulse:
$10^{17}p \rightarrow 10^{18}n$
thermal flux:
$2 \cdot 10^{14} ns^{-1} cm^{-2}$

Present He-II spallation UCN source 🇯🇵



15 UCN/cm^3 E_c = 90 neV, 2008
70 250

PNPI-UCN Source



$C_{UCN} = 2.9 \cdot 10^3$ n/(cm^3 s)

$\Phi = 3.2 \cdot 10^{12}$ n/(cm^2 s)

He @ T=1.2 K

C @ T=20 K

Bi @ T=300 K

$Q_{He} = 6$ W

$Q_{Al} = 13$ W

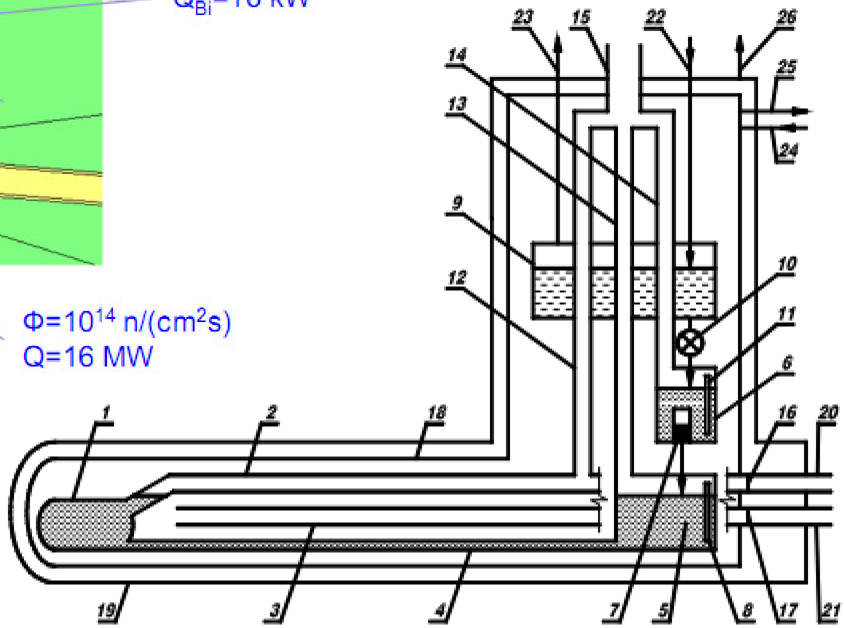
19 W

$Q_C = 750$ W

$Q_{Bi} = 16$ kW

$\Phi = 10^{14}$ n/(cm^{2}s)

Q=16 MW



1 – He II cell; 2 – UCN neutron guide, 3 – CN neutron guide, 4 – He II supply pipe, 5 – lower bath @ 1.2 K, 6 – intermediate bath @ 1.2 K, 7 – ^{3}He filter, 8 – level sensor, 9 – upper bath @ 4.2 K, 10 – helium supply valve, 11 – level sensor, 12 – vacuum pipe (gravitation trap for UCN), 13 – vacuum pipe for lower bath, 14 – vacuum pipe for intermediate bath, 15 – main vacuum manifold, 16 – UCN neutron guide membrane, 17 – CN neutron guide membrane, 18 – thermal shield @ 20 K, 19 – vacuum jacket, 20 – UCN outer neutron guide, 21 – CN outer neutron guide, 22 – helium supply at temperature of 4.2 K, 23 – pipe for helium vapour removal, 24 – helium supply for thermal shield 18, 25 – helium removal from thermal shield 18, 26 – pumping of vacuum jacket.

Project	Site	Method	Production Rate/cc	Converter Volume	Useful Density
UCNA prototype	LANL	Spallation target, SD2	500 UCN/cc/μA (up to 10 μA)	300 cc	n ≤ 150
UCNA production	LANL	Spallation target, SD2	90 UCN/cc/μA (up to 10 μA)	2000 cc	n ≤ 0.15/μA
PULSTAR	NCSU	1-2 MW Reactor, SD2 (CW)	12,000 UCN/cc/MW	1000 cc	n ≤ (50-200)
Mainz/FRM-II	TUM	TRIGA reactor, SD2	22,000/pulse		n=10 n≤10,000
Osaka	Osaka University	Spallation target, LHe	3.5 UCN/cc/μA	12000 cc	n ≤ 5.2
SUNS	PSI	Spallation target, SD2	15,000 UCN/cc/μA (8 mC in 4s/500s)	30,000 cc	n ≤ 2500
PF4	ILL	54 MW reactor, LHe			n ≤ 40
TRIUMF-UCN	TRIUMF	Spallation target, LHe	400 UCN/cc/μA ,400μA		n≤ 42,000
PNPI-UCN	PNPI	Reactor		30,000	n≤ 40,000

Summaries

- Cold Neutron/UCN experiment is truly multidisciplinary.
  - Nuclear physics, condensed matter physics, atomic physics, particle physics
  - Energy scale ranging from peV to TeV.

- UCN can be stored in a well-shielded box for high precision measurements for a long coherence time.

- Many new cold neutron and UCN facilities are coming online this decade
  - Cold Neutron Source: Liquid H_2, D_2, Solid CH_4, Poly, …
  - UCN converter: Superfluid He, Solid D_2, Solid O_2

- Experiments are table-top scale (or a single room size scale)
  - Neutron beta-decay lifetime (Paul Huffman)
  - Neutron beta-decay angular correlation (Stephan Baeβler)
  - Neutron EDM search (Brad Filippone)
  - PV NN interaction (Mike Snow)
  - Neutron Gravity (Abele)