Prospects for an Improved Neutron Lifetime Measurement Using Magnetically Trapped Ultracold Neutrons

K. J. Alvine, C. R. Brome, J. S. Butterworth,
S. N. Dzhosyuk, C. E. H. Mattoni, R. A. Michniak,
D. N. McKinsey, L. Yang and J. M. Doyle
Harvard University

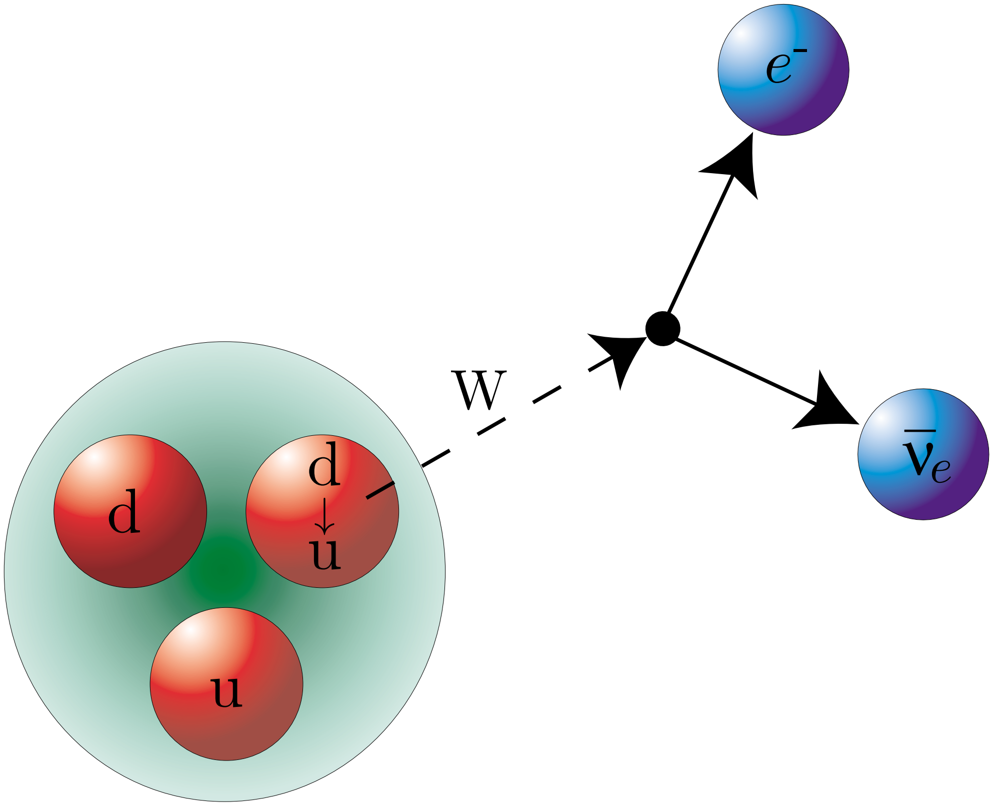
P. R. Huffman, A. K. Thompson and G. L. Yang
NIST, Gaithersburg

K. J. Coakley
NIST, Boulder

R. Golub
HMI, Berlin

S. K. Lamoreaux
Los Alamos National Laboratory

Neutron Beta Decay



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

P. R. Huffman

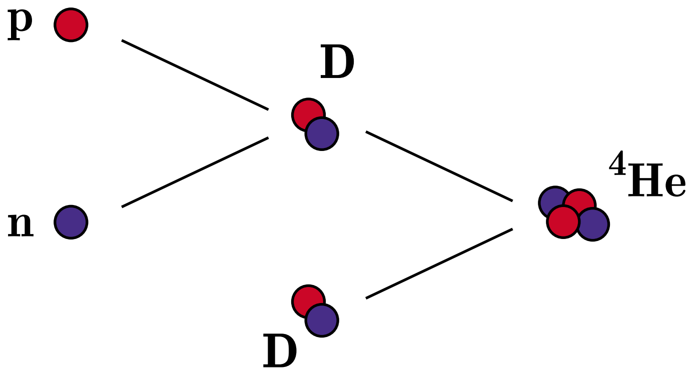
Why Study the Neutron?

The Standard Model

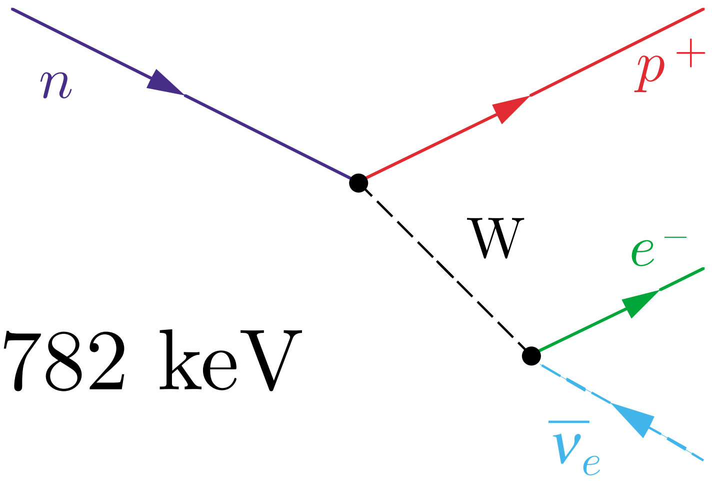
CKM Unitarity

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Big Bang Nucleosynthesis



Neutron Beta Decay



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

$$\frac{\hbar}{\tau_n} \sim (g_v^2 + 3g_a^2)F(E_e)\left[1 + a\frac{p_e \cdot p_\nu}{E_e E_\nu} + \sigma_n \cdot \left(A\frac{p_e}{E_e} + B\frac{p_\nu}{E_\nu}\right)\right]$$

Neutron Beta Decay

$$\tau_n \sim \frac{1}{(g_v^2+3g_a^2)}$$ neutron lifetime

$$\lambda = \frac{g_a}{g_v} \approx -1.27$$

$$A = -2\frac{\lambda^2+\lambda}{1+3\lambda^2} \approx -0.110$$ spin-electron asymmetry

$$B = 2\frac{\lambda^2-\lambda}{1+3\lambda^2} \approx 0.983$$ spin-neutrino asymmetry

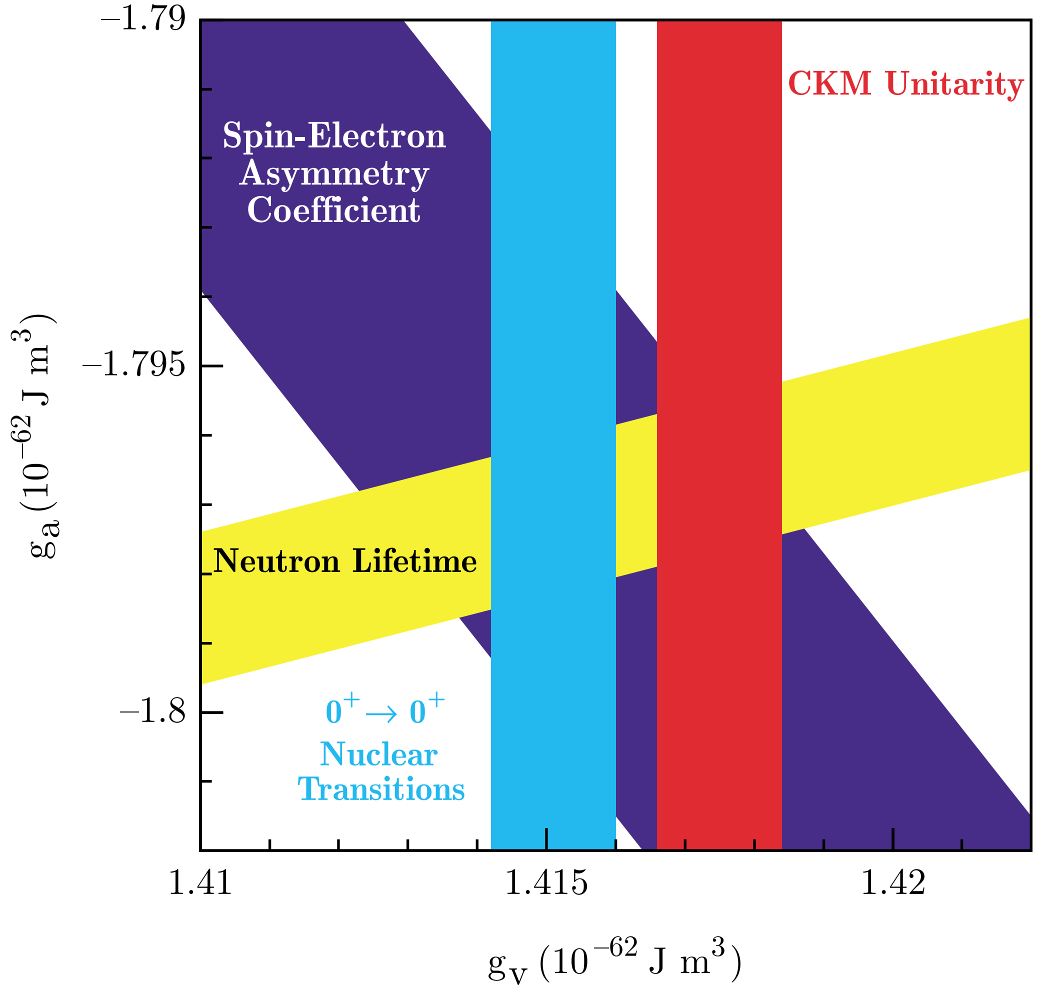
$$a = \frac{1-\lambda^2}{1+3\lambda^2} \approx -0.102$$ electron-neutrino asymmetry

from muon decay

$$\boxed{g_v = V_{ud} G_F}$$

Neutron Beta Decay

From τ_n and λ, one can extract the semileptonic vector and axial-vector coupling constants g_V and g_A.



Big Bang Nucleosynthesis

neutron-proton thermal equilibrium → **nucleosynthesis**

freezeout

Thermal Equilibrium (T > 1 MeV)

- n/p abundance dominated by weak force interactions

$$p + \nu_e \leftrightarrow n + e^+$$

$$n + \nu_e \leftrightarrow p + e^- \qquad n/p \sim e^{-Q/T}$$

Freezeout

- n/p decreases due to neutron decay

$$n \longrightarrow p + e^- + \nu_e \qquad \tau_n = 900 \text{ s}$$

Nucleosynthesis (T~0.1 MeV)

- As the universe expands and cools, these reactions are suppressed and light elements are formed.

$$p + n \longrightarrow d + \gamma$$

$$d + d \longrightarrow {}^4\text{He} + \gamma$$

almost all n's present → ^{4}He

time

decreasing energy

VOLUME 82, NUMBER 21 PHYSICAL REVIEW LETTERS 24 MAY 1999

Sharpening the Predictions of Big-Bang Nucleosynthesis

Scott Burles,[1] Kenneth M. Nollett,[2] James W. Truran,[1] and Michael S. Turner[1,2,3]
[1]Department of Astronomy & Astrophysics, Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637-1433
[2]Department of Physics, The University of Chicago, Chicago, Illinois 60637-1433
[3]NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500

(Received 14 January 1999)

We have reexamined the nuclear inputs to big-bang nucleosynthesis using Monte Carlo realization of the cross-section data to directly estimate theoretical uncertainties for the yields of D, ^{3}He, and ^{7}Li. Our results indicate that previous estimates of the uncertainties were too large by a factor of 2. Using the Burles–Tytler deuterium measurement, we infer a baryon density $\Omega_B h^2 = 0.019 \pm 0.0024$, predict a primeval ^{4}He mass fraction $Y_P = 0.246 \pm 0.0014$, and obtain a limit to the equivalent number of neutrino species $N_\nu < 3.20$ (all at 95% C.L.). We also identify key reactions and the energies, where improved data would allow further progress. [S0031-9007(99)09188-7]

PACS numbers: 26.35.+c, 98.80.Ft

Motivation.—Big-bang nucleosynthesis (BBN) is an observational cornerstone of the hot big-bang cosmology. For more than two decades the predicted abundances of the light elements D, ^{3}He, ^{4}He, and ^{7}Li have been used to test the consistency of the hot big-bang model at very early times ($t \sim 0.01-200$ s) [1,2]. The state of affairs in 1995 was summarized by a concordance interval for the baryon density, $\Omega_B h^2 = 0.007-0.024$, for which the predicted abundances for all four light elements were consistent with the observational data [1]. In addition to testing the standard cosmology, BBN also gave the best determination of the baryon density and was the linchpin in the case for nonbaryonic dark matter.

The big-bang abundance of deuterium is most sensitive to the baryon density [3], making it the "baryometer." However, deuterium is fragile and is destroyed by stars even before they reach the main sequence. Thus, local measurements, where probably about 50% of the material has been through stars, do not directly reflect its primeval abundance. Recently, the situation has changed dramatically. Burles and Tytler measured the deuterium abundance in high-redshift hydrogen clouds, where it is expected that almost none of the material has been processed through stars, and they have made a strong case for a primeval deuterium number density, $(\mathrm{D/H})_P = (3.4 \pm 0.25) \times 10^{-5}$ [4,5]. Their measurement has opened the door to a precision era for BBN [2].

From this 10% measurement of $(\mathrm{D/H})_P$, the baryon density can be inferred to about 10%, at $\Omega_B h^2 = 0.019$, or in terms of baryon-to-photon ratio, $\eta = 5.1 \times 10^{-10}$. With the baryon density in hand, one can predict the abundances of the other three light elements. Then, ^{4}He and ^{7}Li can test the consistency of BBN, D and ^{3}He can probe stellar processing since BBN, and ^{7}Li can test stellar models. Furthermore, a precise determination of the baryon density can make BBN an even sharper probe of particle physics (e.g., the limit to the number of light particle species).

To take full advantage of BBN in the precision era requires accurate predictions. The uncertainty in the deuterium-inferred baryon density comes in almost equal parts from the (D/H) measurement and theoretical error in predicting the deuterium abundance. The BBN yields depend upon the neutron lifetime and eleven nuclear cross sections (see Table I). In 1993, Smith, Kawano and Malaney (SKM) estimated the theoretical uncertainties [6]. While their work has set the standard since, it is not without its shortcomings: Treatment of systematic effects and correlated errors was neither uniform nor explicit. More importantly, data sets were not simply weighted by their reported errors; rather, subjective uncertainties were attached to *ad hoc* theoretical fits on the basis of scatter among the experiments. Finally, there have been new measurements [7–9].

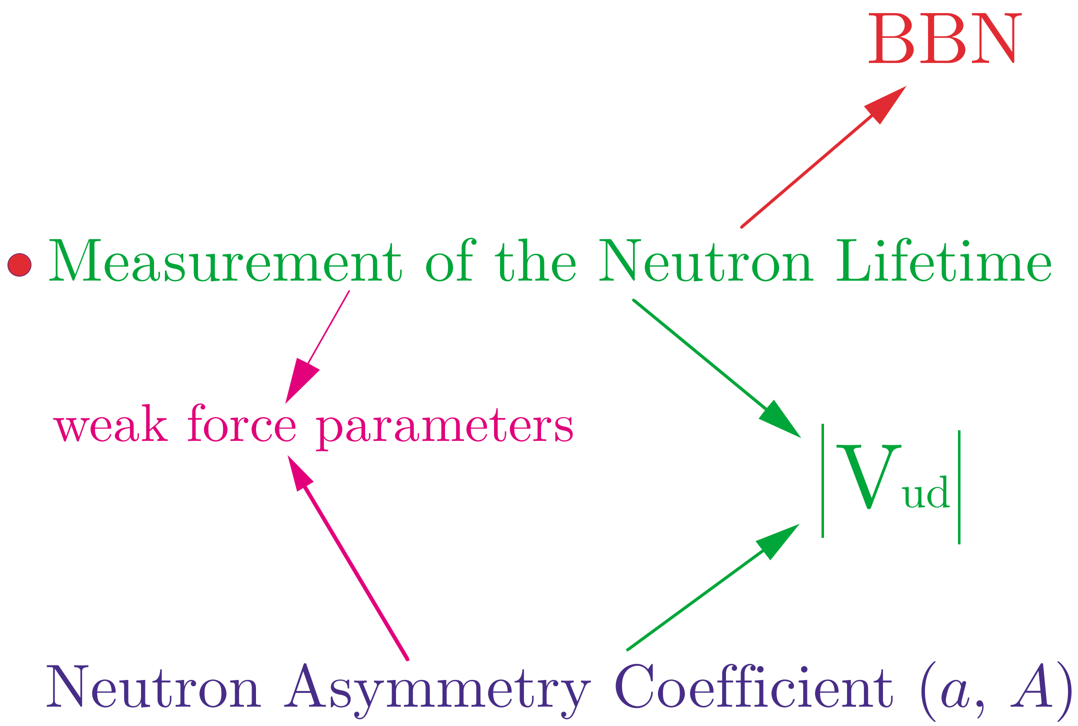
After a careful analysis and updating of the microphysics for small but important effects, the theoretical uncertainty in the predicted ^{4}He abundance has been reduced essentially to that in the neutron lifetime, $\Delta Y_P = \pm 0.001$ (95% C.L.) [10]. Motivated by the primeval deuterium measurement, we decided to refine the error estimates for the other light elements, using the nuclear data themselves and

TABLE I. For each reaction and nuclide, the energies (in keV, center of mass) at which the sensitivity functions for D and ^{7}Li attain half their maximum value; these intervals indicate the energies relevant for BBN ($\Omega_B h^2 = 0.019$).–

Reaction	D	^{7}Li
$p(n,\gamma)d$	25–200	17–153
$d(p,\gamma)^3$He	53–252	65–270
$d(d,p)^3$H	55–242	134–348
$d(d,n)^3$He	62–258	79–282
^{3}He$(\alpha,\gamma)^7$Be	No effect	157–376
^{3}He$(d,p)^4$He	187–325	107–283
^{3}He$(n,p)^3$H	52–228	24–188
^{7}Li$(p,\alpha)^4$He	No effect	57–208
^{7}Li$(p,n)^7$Be	No effect	1649–1690
^{3}H$(\alpha,\gamma)^7$Li	No effect	62–162
^{3}H$(d,n)^4$He	176–338	167–285

Goals

- Magnetic Trapping of Neutrons



BBN

- Measurement of the Neutron Lifetime

weak force parameters

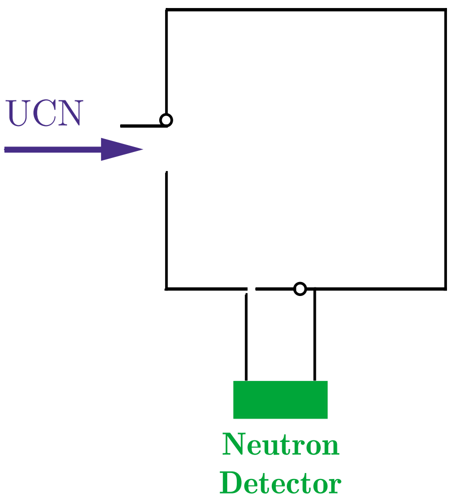
$\left|V_{\mathrm{ud}}\right|$

Neutron Asymmetry Coefficient (a, A)

Previous Neutron Lifetime Measurements

Fill and Dump

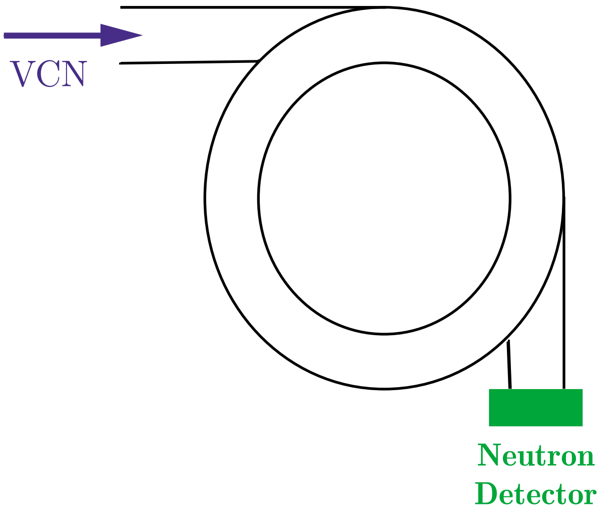
Material Walled Bottle



$\tau_n = 885.7$ s ± 1.0 s

(wall losses)

Magnetic Storage Ring



$\tau_n = 877$ s ± 10 s

(betatron oscillations)

Beam

$\tau_n = 889.2$ s ± 4.8 s

(flux measurement)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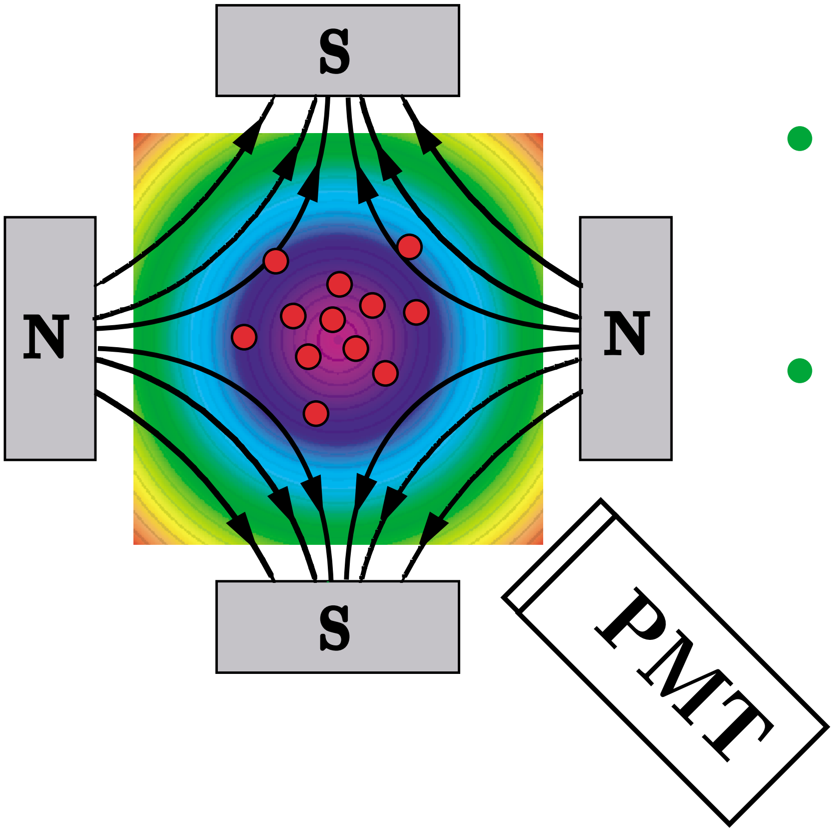
Magnetic Trapping of UCN

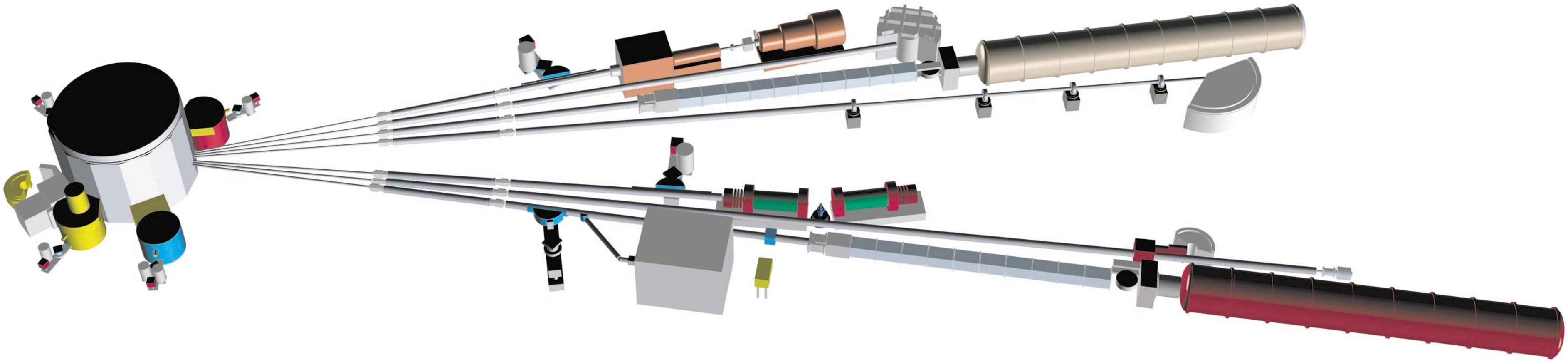


- Produce UCN using superthermal scattering
- Confine UCN with a magnetic trap
- Detect UCN by measuring beta-decay rate as a function of time.

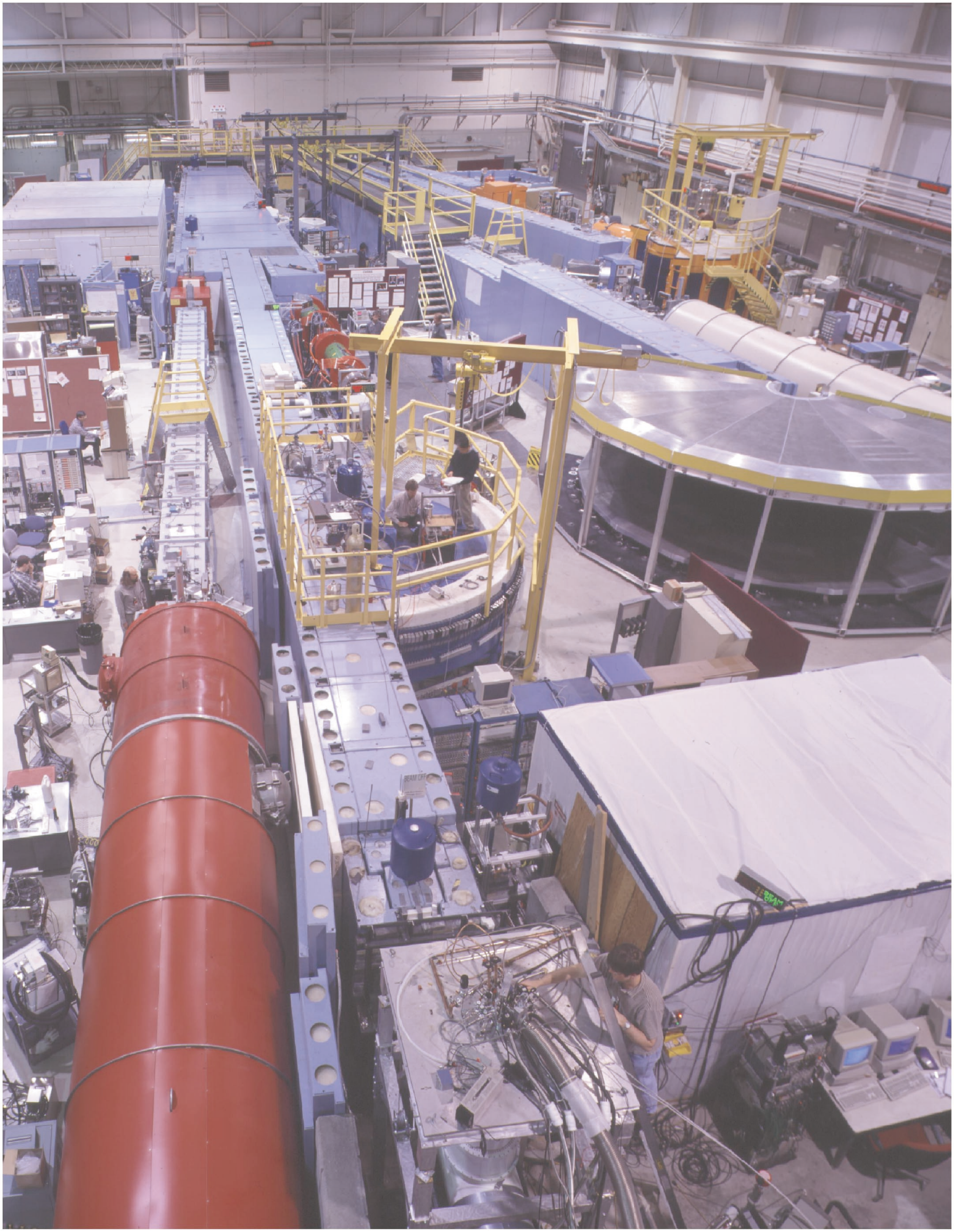
Why Trap?

- Longer interaction times
- Eliminates systematic effects present in previous experiments

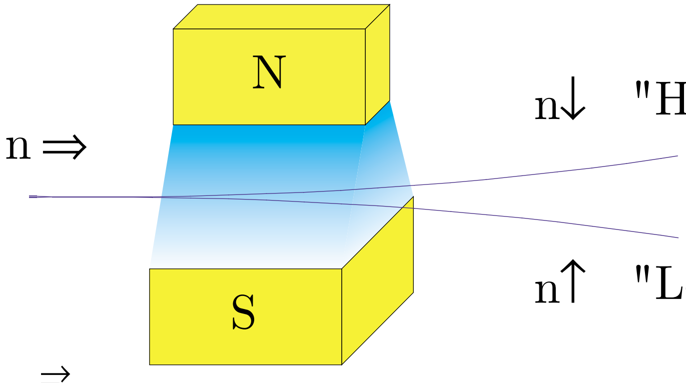
NIST Center for Neutron Research



- 20 MW split-core research reactor
- Liquid hydrogen cold source
- Eight cold neutron guides, one for fundamental physics
- 1 x 10^9 n/cm^2/s at end of fundamental physics guide



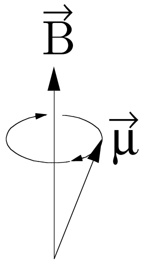
Magnetic Trapping



n↓ "High Field Seekers"

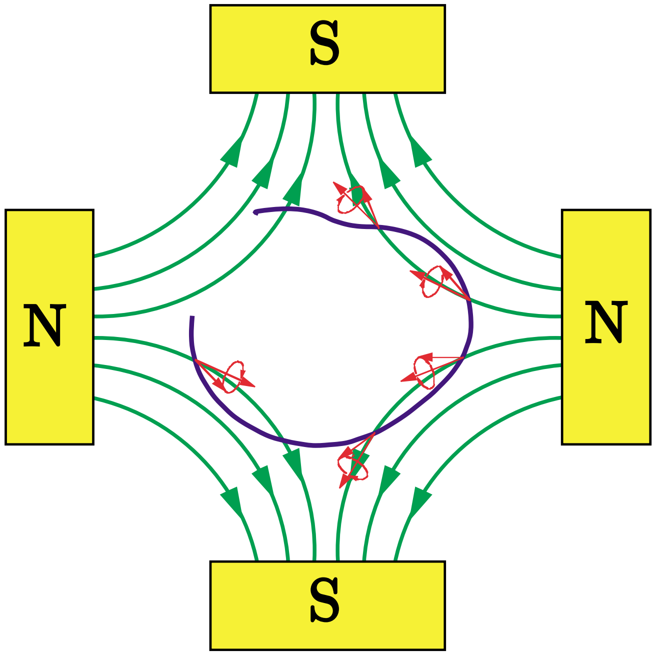
$F = \nabla\,(\vec{\mu} \bullet \vec{B})$

n↑ "Low Field Seekers"



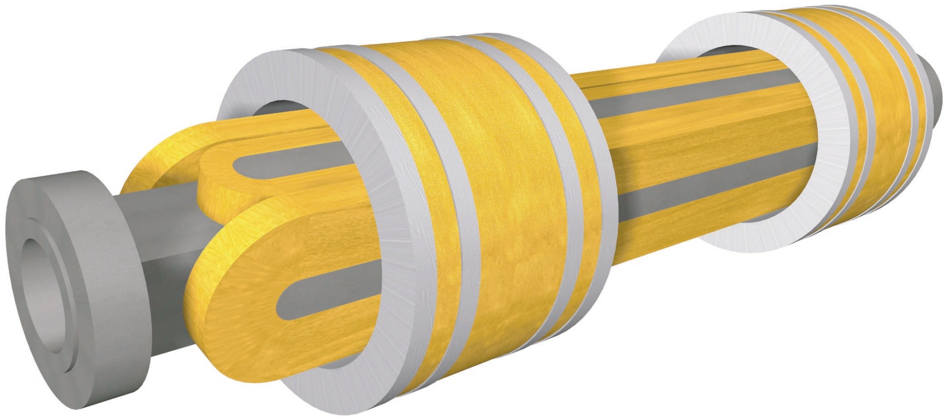
$$\frac{d\vec{\mu}}{dt} = \gamma\,\hat{\mu} \times \vec{B}$$

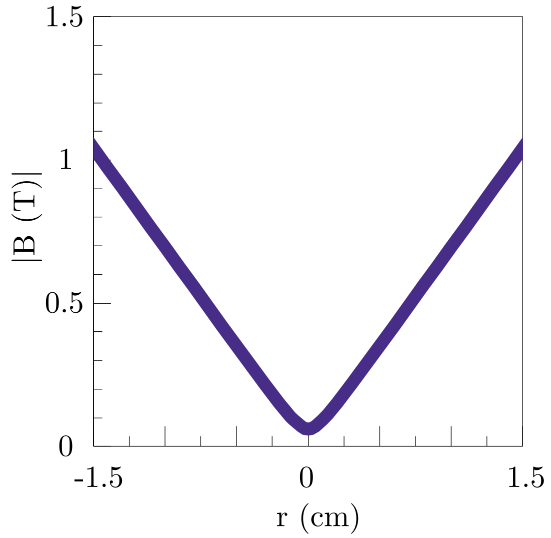
Larmor Frequency γB

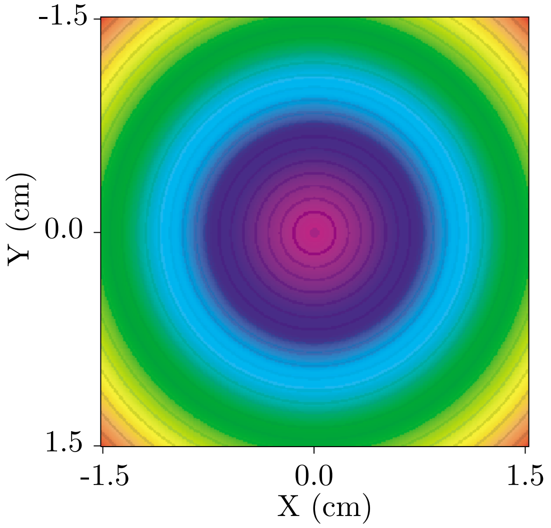


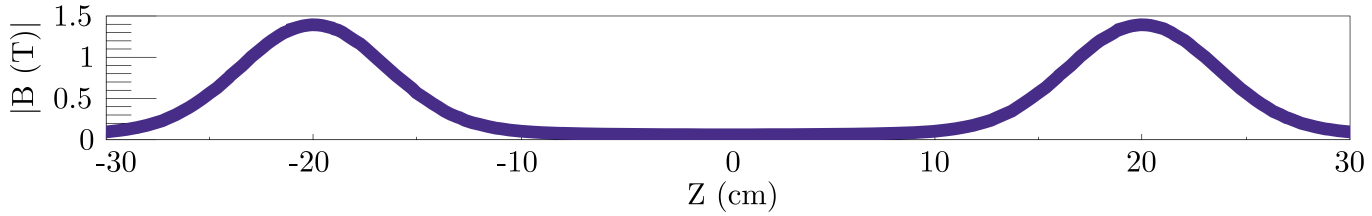
Spin follows magnetic field if $\gamma B >> \dfrac{\frac{dB}{dt}}{B}$

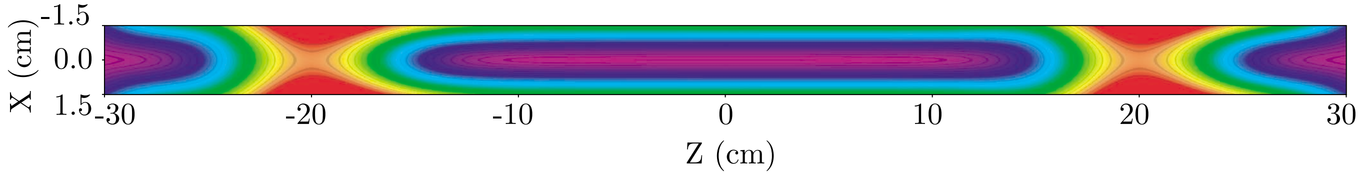
Ioffe-Type Magnetic Trap

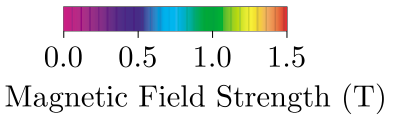












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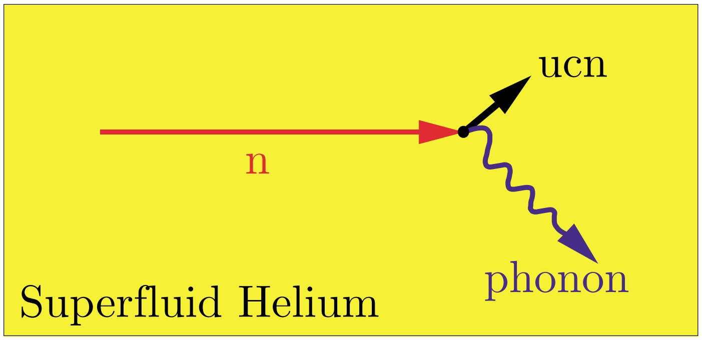
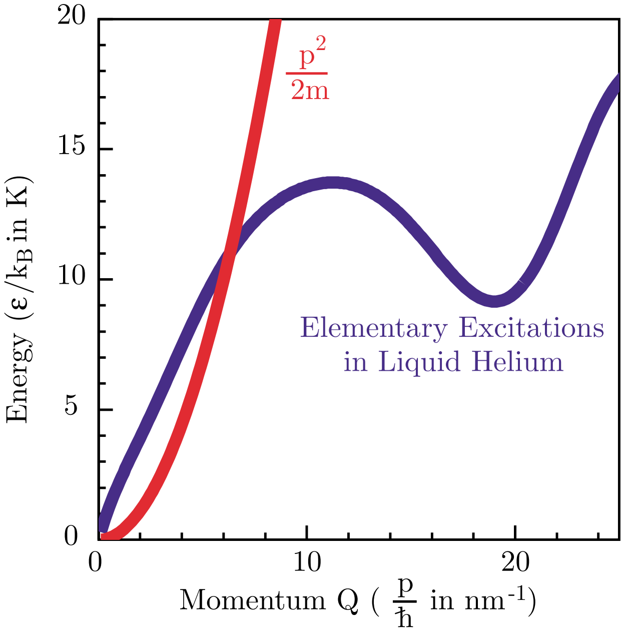
Loading the Trap



$$\vec{p}_{ucn} = \vec{p}_n - \vec{q}_{phonon}$$

$$E_{ucn} = E_n - E_{phonon}$$

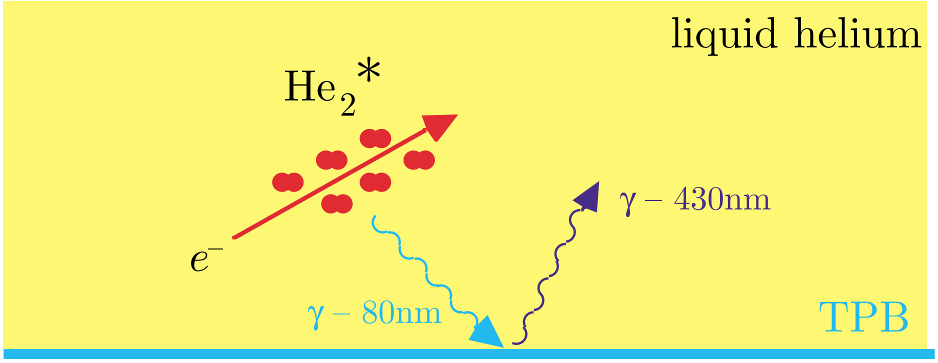


- Neutrons of energy E ≈ 0.95 meV (11 K or 0.89 nm) can scatter in liquid helium to near rest by emission of a single phonon.

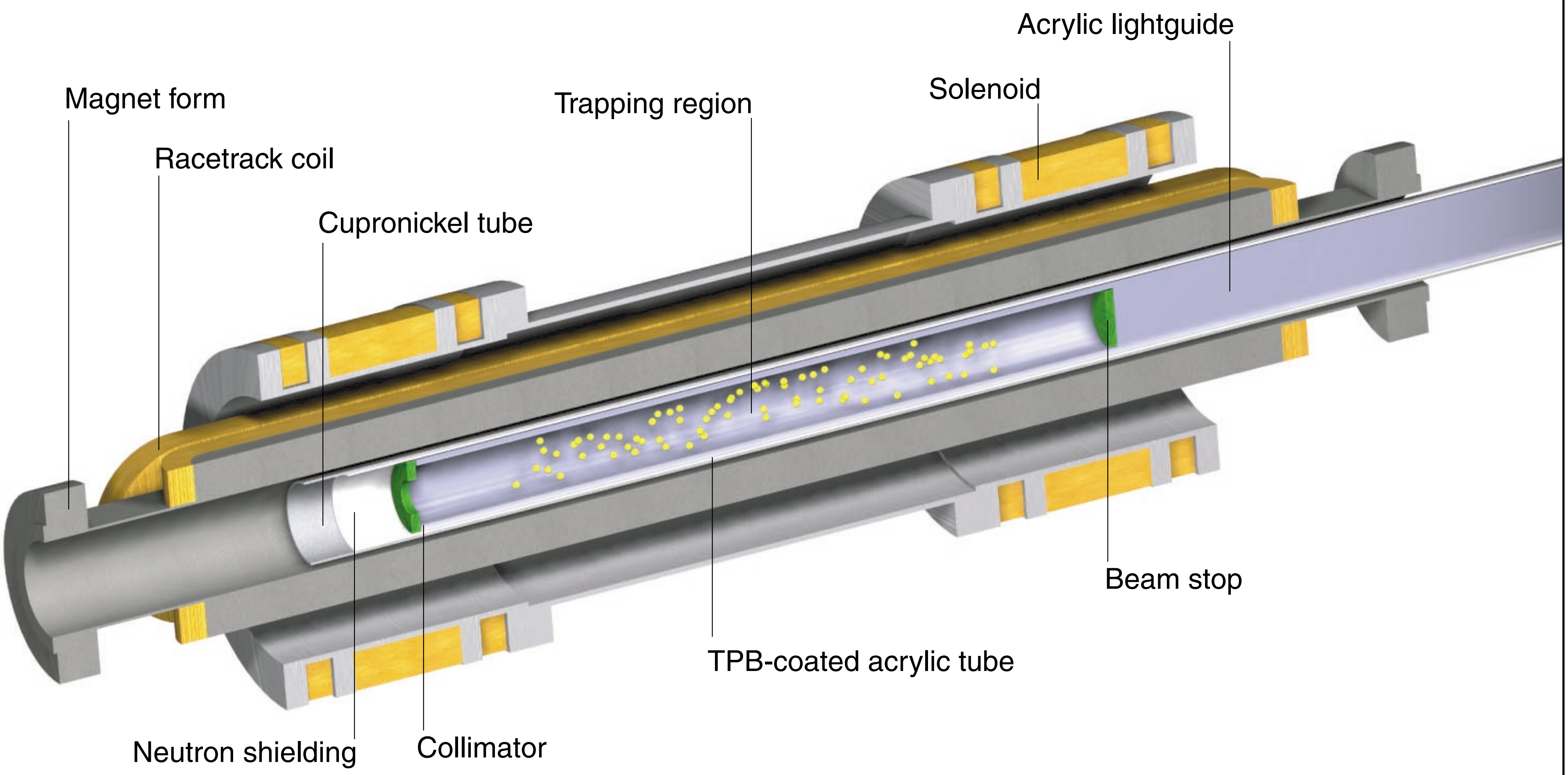
- Upscattering (by absorption of an 11 K phonon) $\propto$ Population of 11 K phonons ~ $e^{-11K/T_{bath}}$

Detection of Trapped Neutrons

$$n \rightarrow p^{+} + e^{-} + \overline{\nu}_e$$



- Recoil electron creates an ionization track in the helium.
- Helium ions form excited He$_2$* molecules (ns time scale) in both singlet and triplet states.
- He$_2$* singlet molecules decay, producing a large prompt (<20 ns) emission of extreme ultraviolet (EUV) light.
- EUV light (80 nm) converted to blue using the organic fluor TPB (tetraphenyl butadiene).



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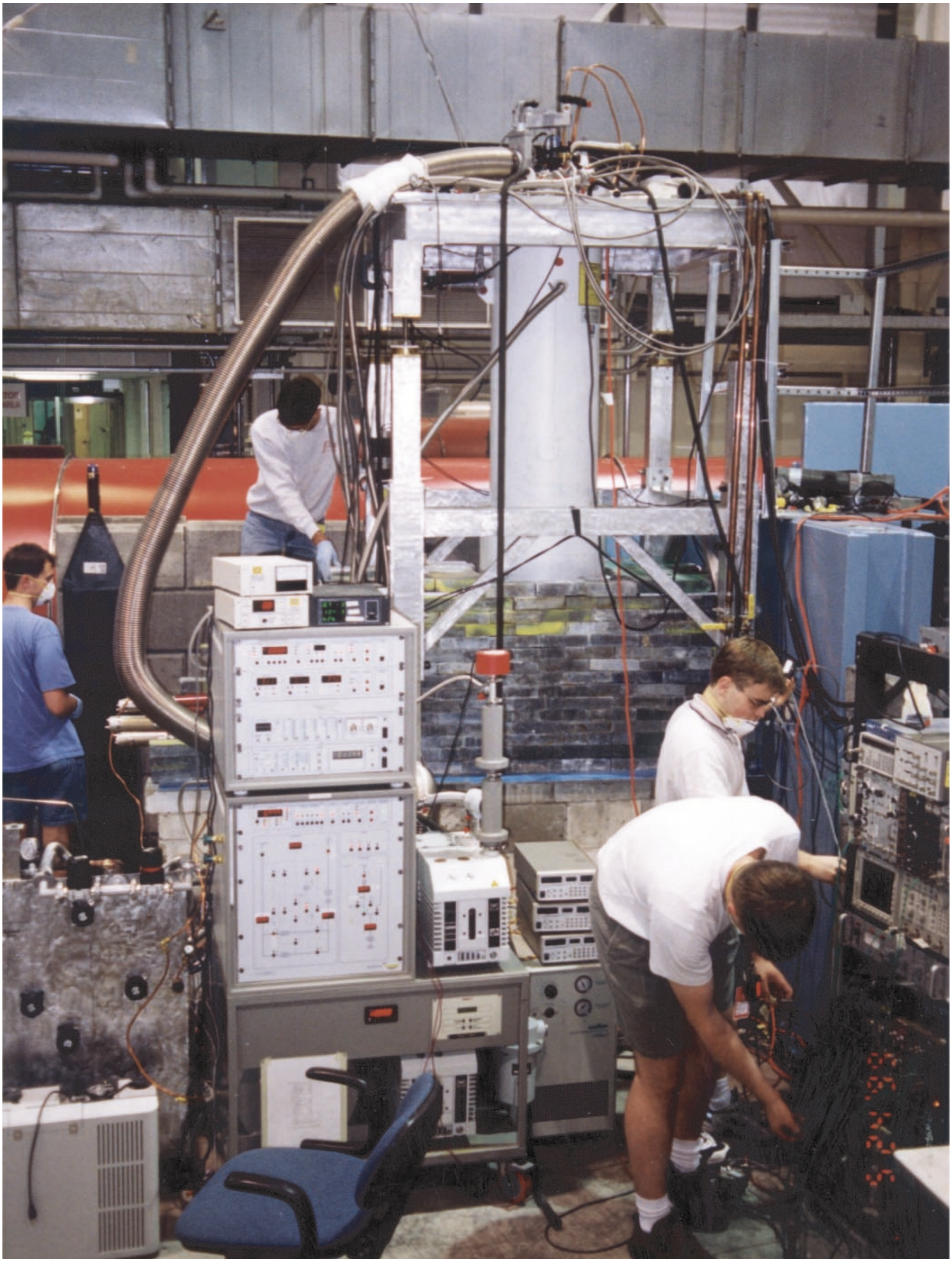


Raw Data

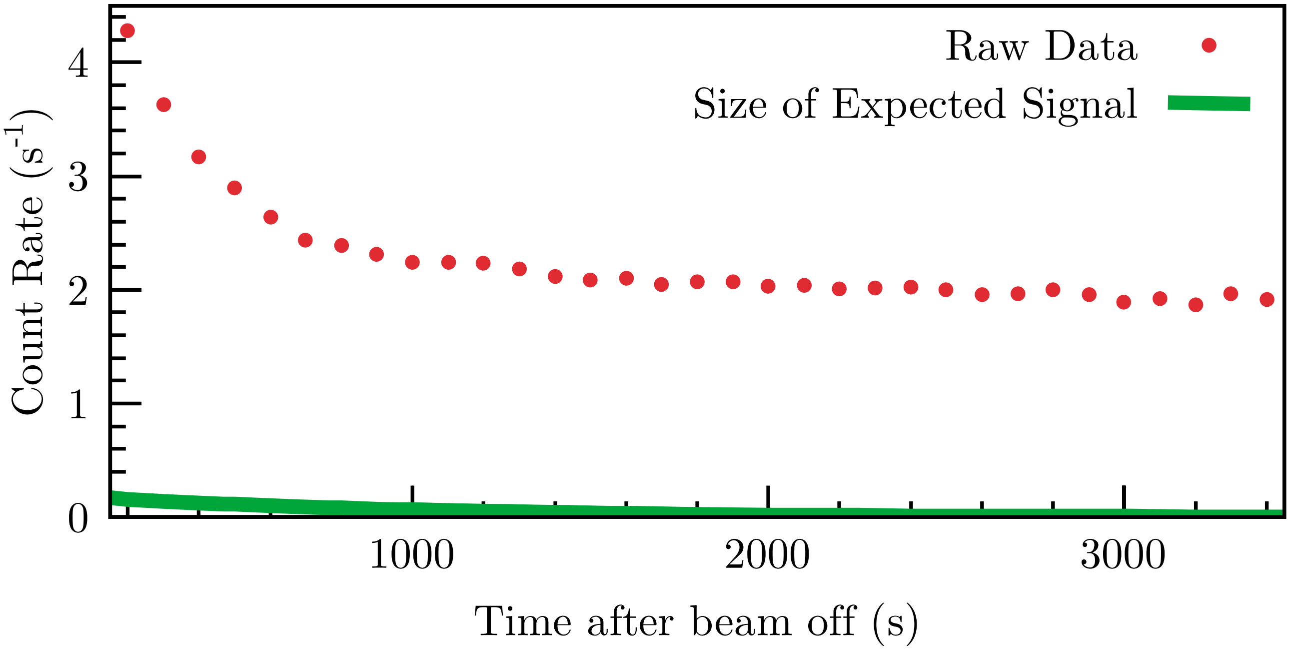
Expected Signal:

- Trapped neutrons ~0.2 Hz

480 neutrons trapped, per load

÷ 885 s = 0.54 decays/s

x 31% = 0.17 counts/s

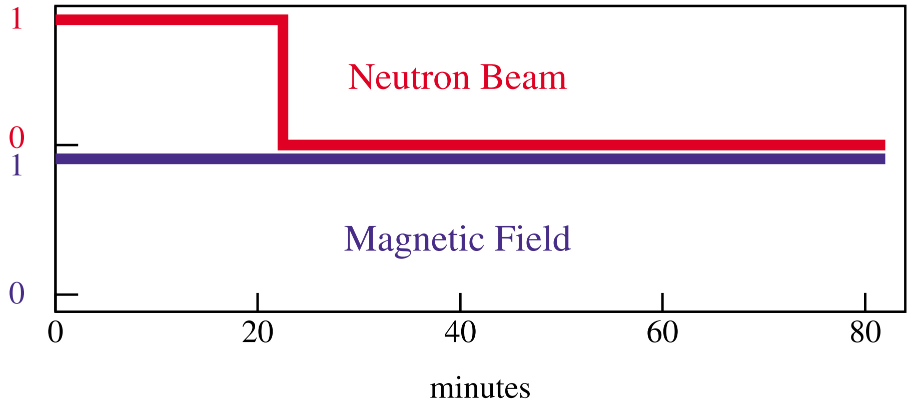


Backgrounds:

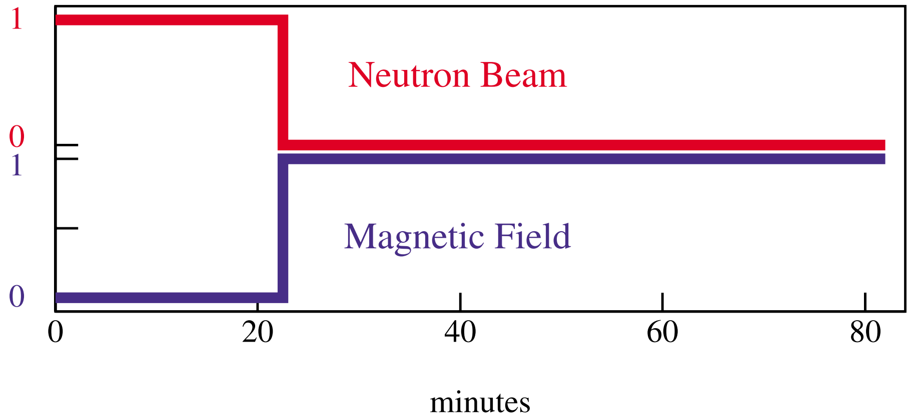
- Constant
  - γ's, fast neutrons
  - cosmic rays
  - natural radioactivity
  - long τ activation
  - ~2 Hz
- Time-varying
  - materials activation
  - luminescence
  - ~4 Hz Initial

Background Subtraction

"Positive" (trapping) – magnet on during entire run



"Negative" (non-trapping) – magnet off during loading,
on during observation

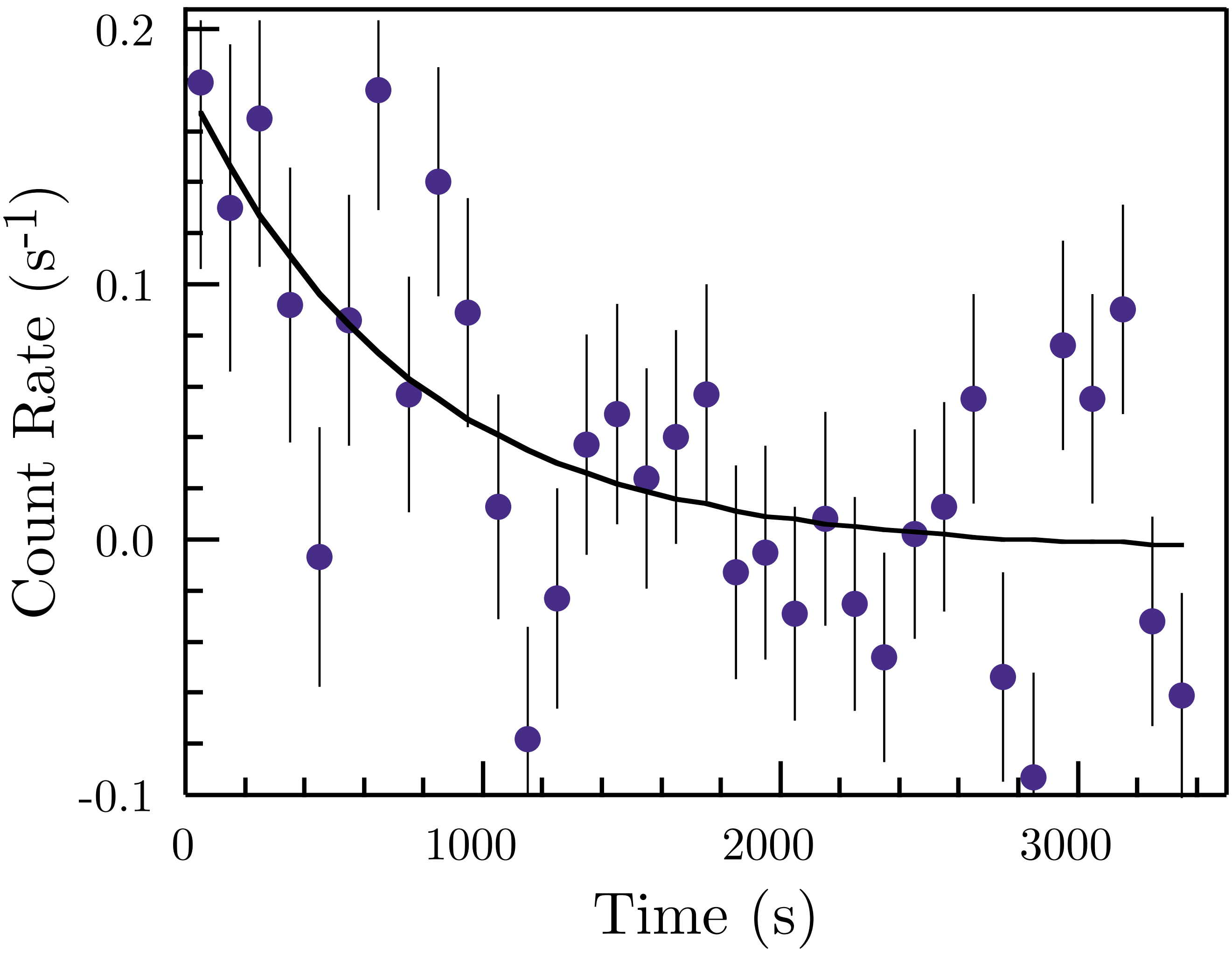


Subtract "Negative" runs from "Positive" runs

Eliminates constant background

Eliminates magnet-independent
time-varying backgrounds
(for example, activation)

Difference Between "Positive" and "Negative"



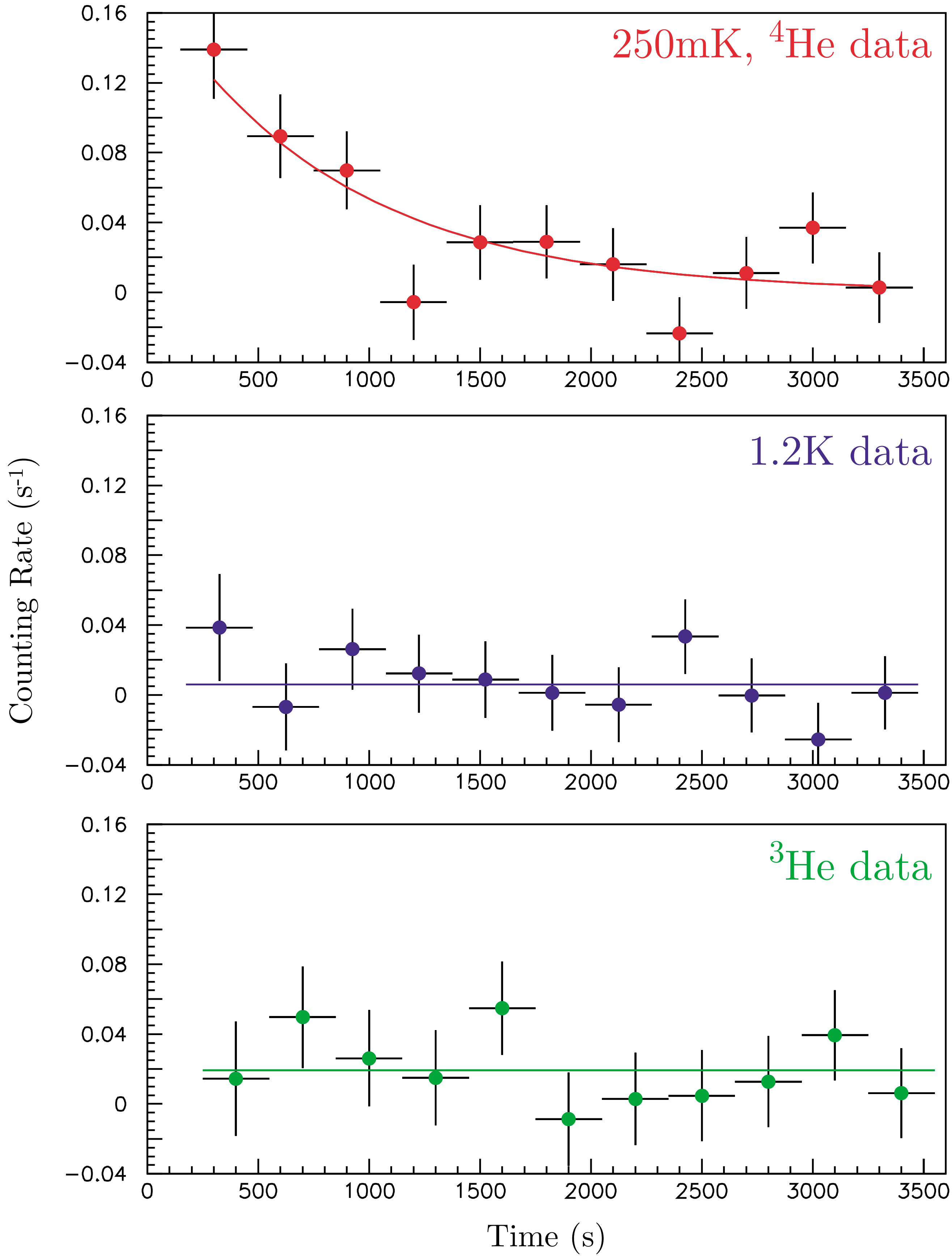
Looks like Trapped Neutrons.... better check!

- Warming helium should remove UCN via thermal upscattering with 11 K phonons

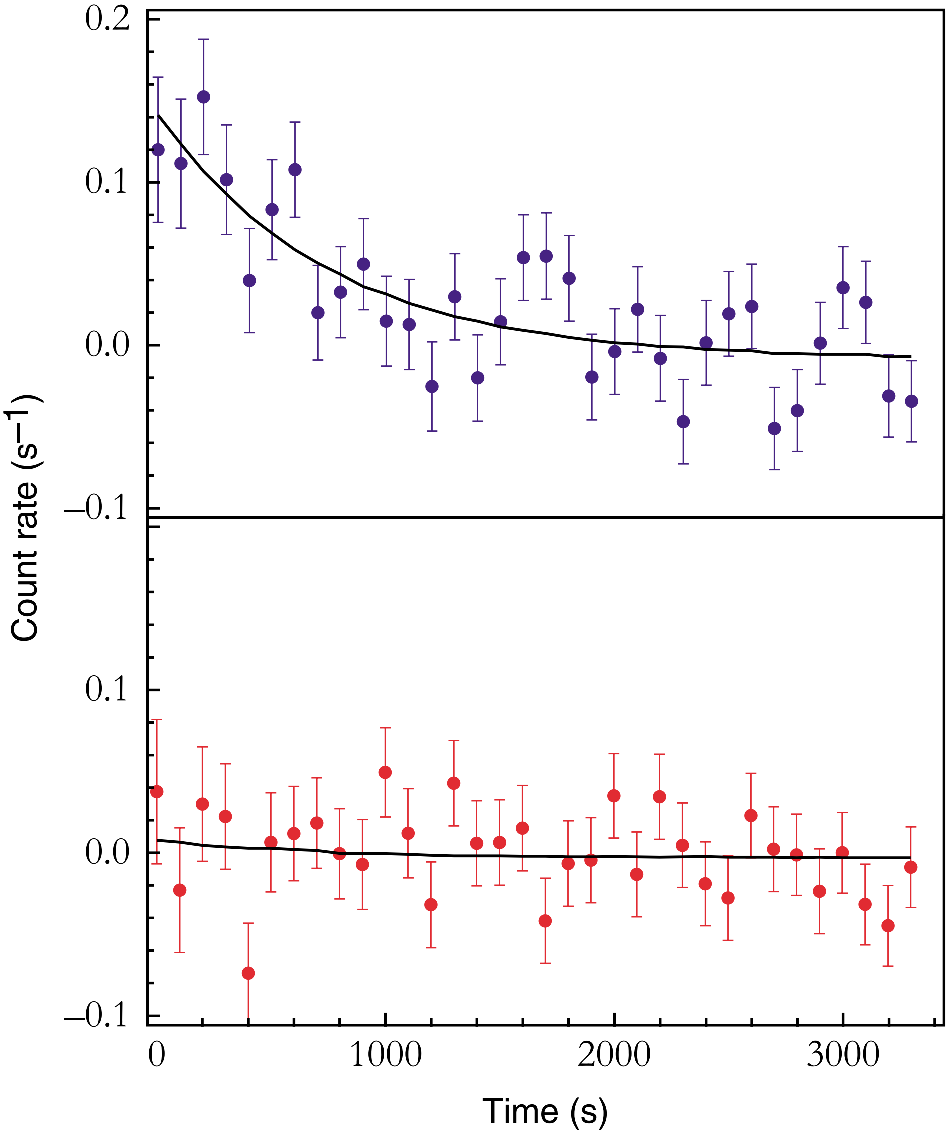
  at just 1.2 K, trapped UCN should be upscattered in less than 1 second

- Doping the isotopically pure ^{4}He with ^{3}He should absorb the UCN

  with just 2 x 10^{-7} concentration of ^{3}He/^{4}He, trapped UCN should be absorbed in less than 1 second with a negligible change to any background.



250mK, ^{4}He data
1.2K data
^{3}He data
Counting Rate (s^{-1})
Time (s)
0.16
0.12
0.08
0.04
0
−0.04
0
500
1000
1500
2000
2500
3000
3500



$$W_1 = a_1\, e^{-t/\tau} + C_1$$

$$W_2 = a_2\, e^{-t/\tau} + C_2$$

Trapping data (blue):

$a = 0.16\ \mathrm{s}^{-1} \pm 0.03\ \mathrm{s}^{-1}$

$C = 0.003 \pm 0.007$

$\tau = 660\ \mathrm{s}\ +290\ \mathrm{s}/-170\ \mathrm{s}$

^{3}He data (red):

$a = -0.040\ \mathrm{s}^{-1} \pm 0.045\ \mathrm{s}^{-1}$

$C = -0.011 \pm 0.011$

τ = fixed at 750 s

Total number trapped:

$N = 453 \pm 100$

Theory Predicts:

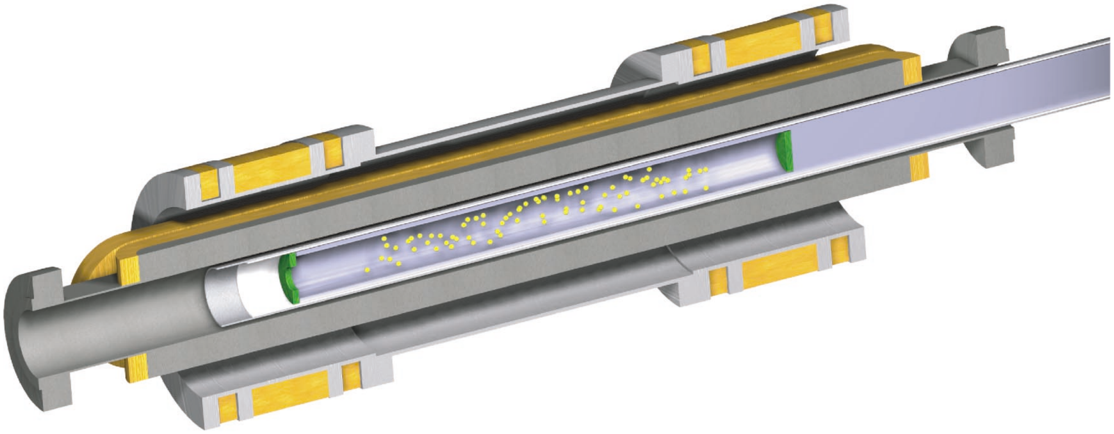
$N = 500 \pm 170$

Evidence for Trapping

- in 250 mK ^{4}He runs, there is a signal, i.e. positive $\neq$ negative
- Signal fits well to single exponential
- Lifetime from fit consistent with τ_n
- Magnitude (number trapped) agrees well with theoretical models
- Magnitude scales as predicted with changing magnetic trap depth
- Signal vanishes when $T > 1$ Kelvin
- Signal vanishes when $f(^3\mathrm{He}) > 10^{-7}$

How Do We Increase the Statistics?

- Increase the number of trapped neutrons by building a larger, deeper magnetic trap
  - Scales with magnetic field as $B^{3/2}$
  - Scales with the trap radius faster than r^2
  - Scales with length

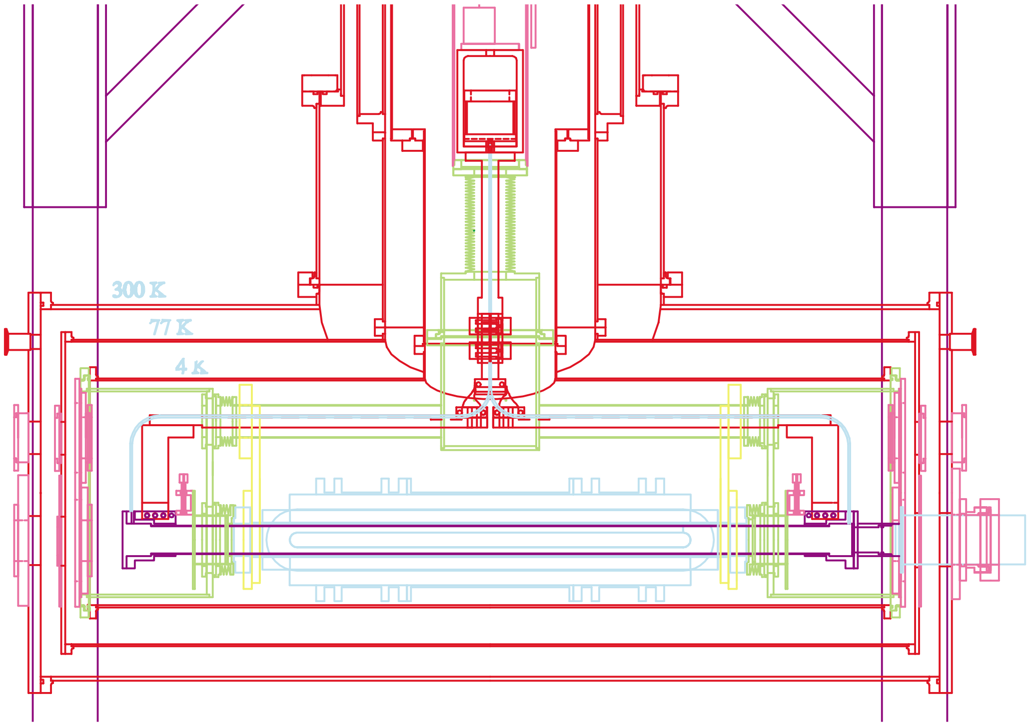


- Increase the detection efficiency
  - Larger diameter cell → higher efficiency
- Increase the incident neutron flux
  - Move closer to source, cold source upgrade
- Reduce backgrounds
  - Wavelength filters or monochromators

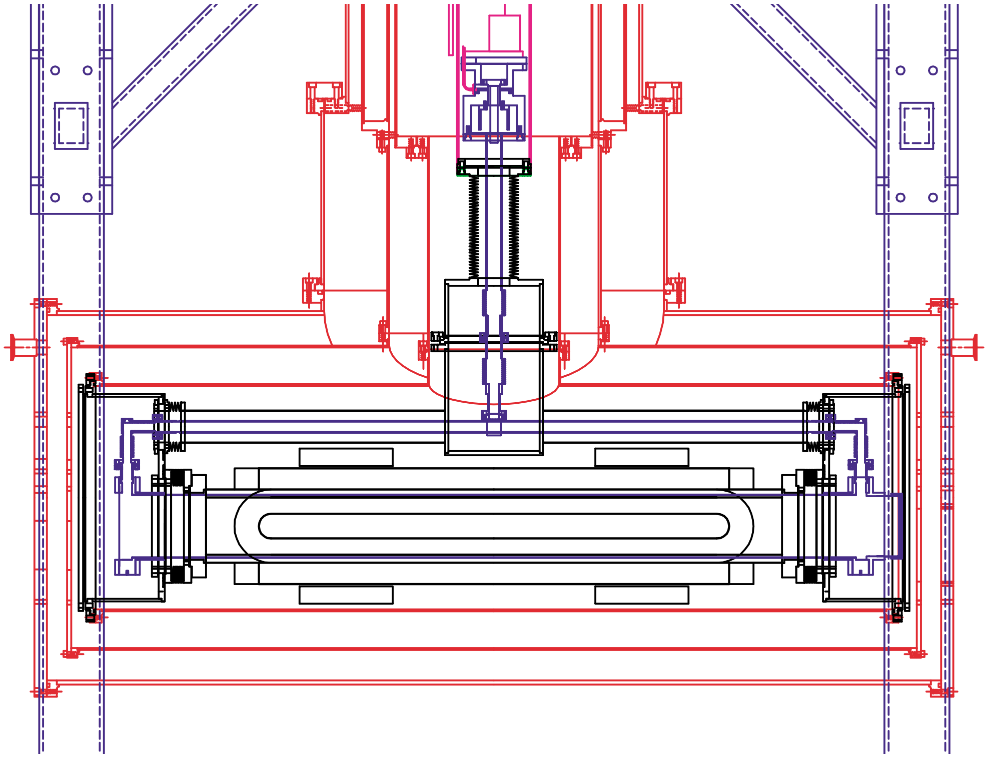
Larger, Deeper Magnet

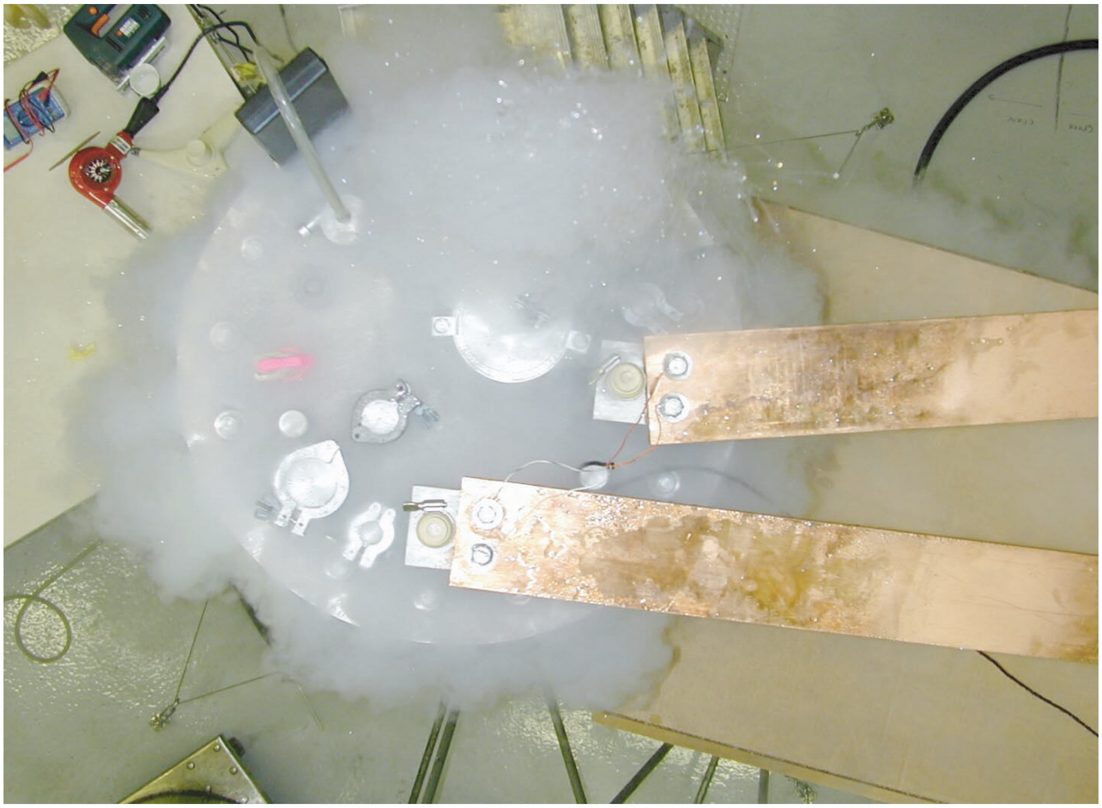
- Present Magnet (proof-of-principle):
  - $\varnothing_{\text{Magnet}} = 5.1$ cm
  - $\varnothing_{\text{Trap}} = 3.2$ cm, $L = 30$ cm
  - $B_{\text{Trap}} = 1.1$ T, $I_{\text{Trap}} \sim 200$ A
- Large low-current design (AMI) which will fit into our present dewar
  - $\varnothing_{\text{Magnet}} = 10.5$ cm
  - $\varnothing_{\text{Trap}} = 7.6$ cm, $L = 27$ cm
  - $B_{\text{Trap}} = 2.3$ T, $I_{\text{Trap}} \sim 200$ A
- Accelerator quadrupole (on loan from KEK, new dewar)
  - $\varnothing_{\text{Magnet}} = 14$ cm
  - $\varnothing_{\text{Trap}} = 11.4$ cm, $L = 39$ cm
  - $B_{\text{Trap}} = 4.4$ T, $I_{\text{Trap}} \sim 3000$ A

Original Apparatus



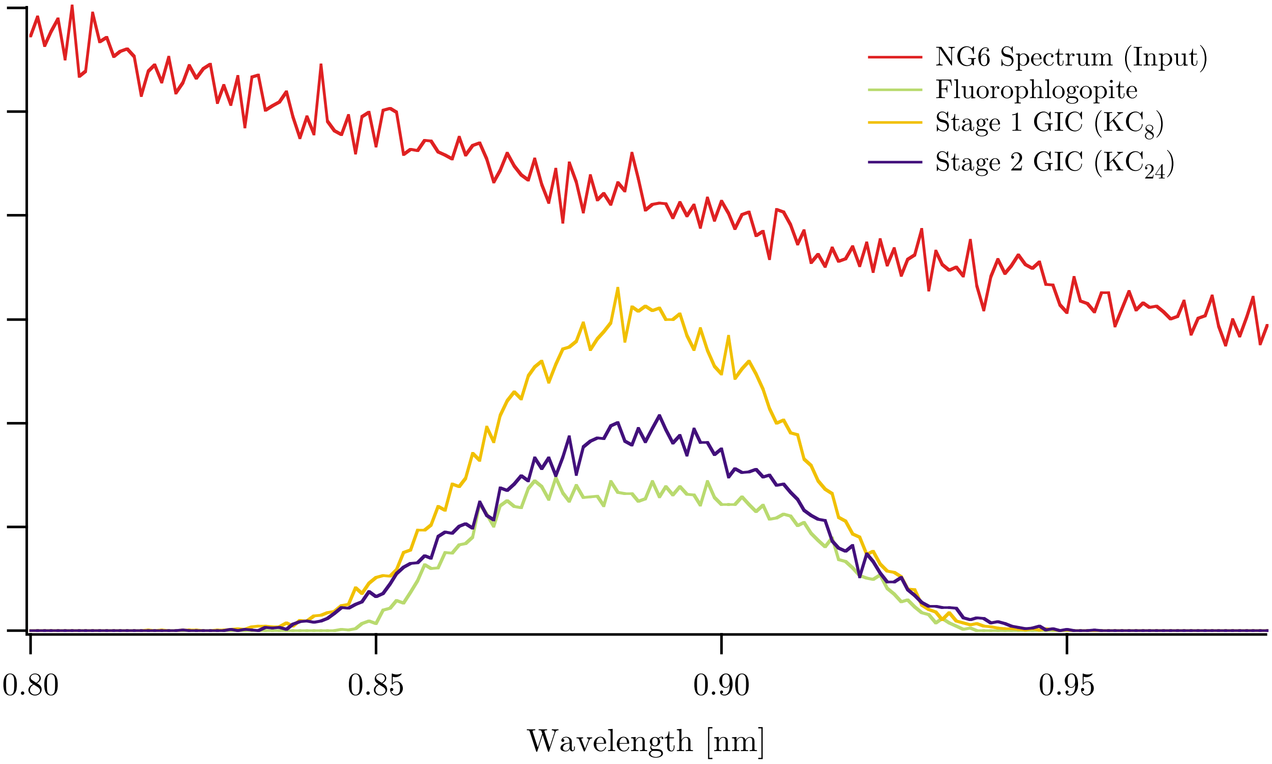
Current Apparatus



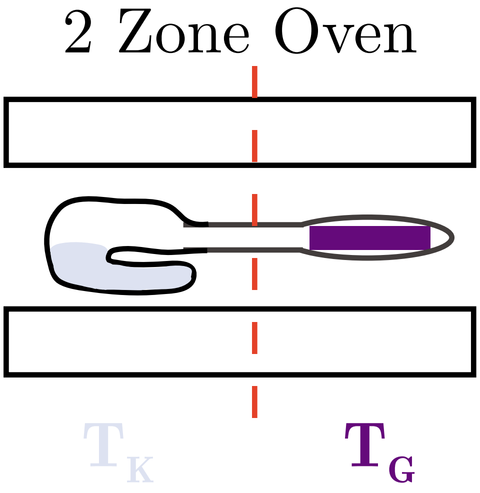


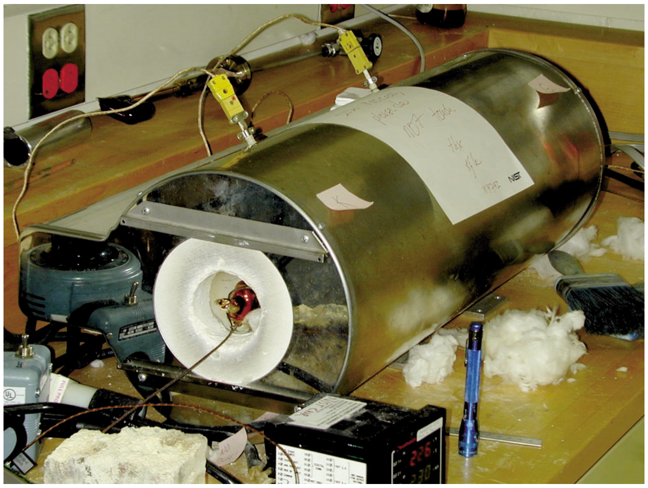
0.9 nm Monochromator

Material	KC_8	KC_{24}	Fluorophlogopite
d (nm)	0.535	0.874	0.9963
θ_{Bragg}	56.3°	30.6°	26.5°
Measured samples:			
β (mosaic)	3.9°	2.2°	0.05° – 0.35°
0.89 nm peak reflectivity (%)	70	51	30



Stage 2 GIC Fabrication



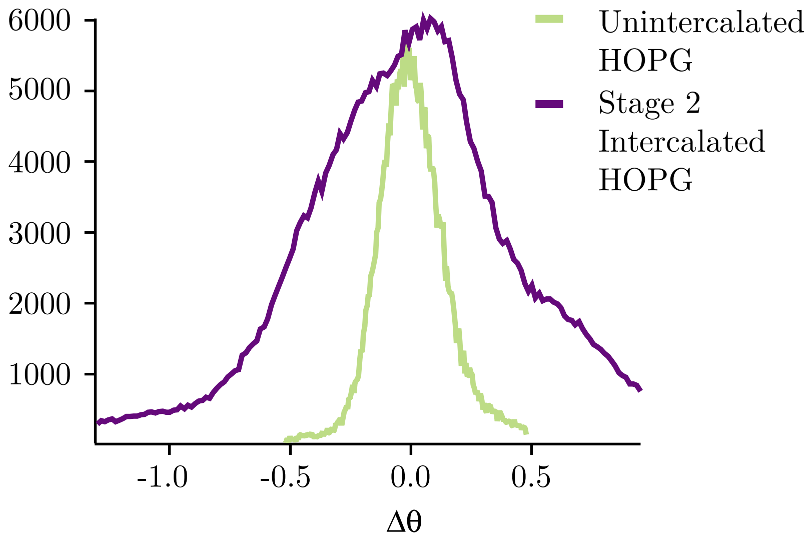


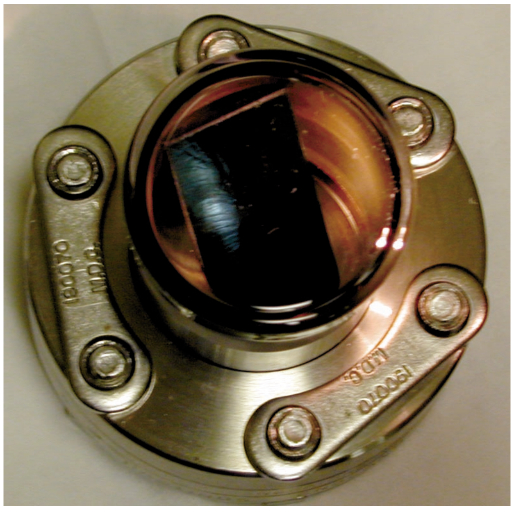
$T_K = 200°C \quad T_G = 320\ °C$

Intercalation to Stage 2 takes 4 Days

Final Mosaic ~1 Degree

X-Ray Diffraction Measurements





What are Our Systematics?

- Absorption by ^{3}He
  - Isotopically pure (10^{-15}) ^{4}He
  - Purified using the heat flush technique
  - $\tau_{\mathrm{loss}} \approx 1.2$ years
- Marginal Trapping
  - Lowering B_0 to $0.3B_0$ and raising back to B_0 throws away 50% of the trapped UCN, and all marginally trapped neutrons.
- Majorana (Spin-Flip) Transitions
  - Bias Field (i.e. no zero-field regions)
  - currently, $\tau_{\mathrm{loss}} \approx 1$ day, w/ no bias
- Thermal (phonon) Upscattering

  $T = 250$ mK $\Rightarrow \tau_{\mathrm{loss}} \approx 3.6$ days

  $T = 100$ mK $\Rightarrow \tau_{\mathrm{loss}} \approx 6$ years

Upgrade Estimates

- Low Current Magnet ($B_{\mathrm{Trap}} = 2.3$ T)
  (no cold source upgrade; monochromator placement as of 10/2000)

Beam	# Trapped	σ_{τ_n} (39 d)
White	7.5 k	3.4 s
KC_{24}	7.0 k	3.2 s

- Accelerator Quadrupole ($B_{\mathrm{Trap}} = 4.4$ T)
  (includes cold source upgrade; permanent monochromator installation)

Beam	# Trapped	σ_{τ_n} (39 d)
White	136 k	0.3 s
KC_{24}	166 k	0.2 s

Conclusions

- UCN produced, stored and detected in one location for the first time
- Approximately 500 UCN trapped per load; polarized UCN density of 1.8 /cm^3
- Magnetic Trapping of UCN:
  - Improved measurement of τ_n
  - Neutron EDM experiment
  - Other experiments?
- With upgrade in progress: (~1 year)
  - ~50x detected trapped UCN (~5x density)
  - τ_n measurement of ± 2 – 3 s (statistics)
- Systematic errors from known trap losses should be of order ± 0.01 s