Using Magnetically Trapped Ultracold Neutrons (UCN) to Measure the Neutron Lifetime

P. R. Huffman, A. K. Thompson, G. Yang, and K. J. Coakley
National Institute of Standards and Technology

S. N. Dzhosyuk, C. E. H. Mattoni, S. Maxwell,
D. N. McKinsey, L. Yang and J. M. Doyle
Harvard University

R. Golub, E. Korobkina
HMI, Berlin

S. K. Lamoreaux
Los Alamos National Laboratory

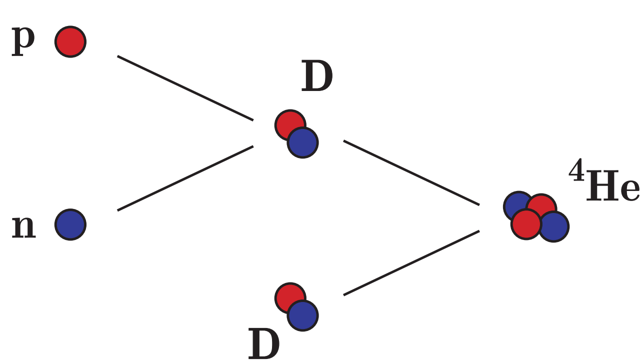
Why Study the Neutron?

The Standard Model

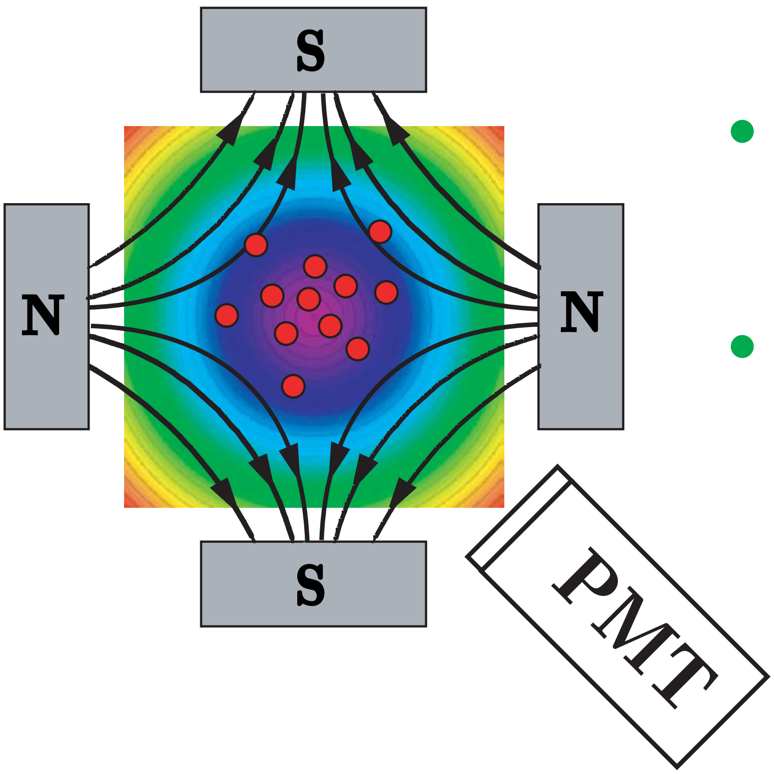
CKM Unitarity

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

Big Bang Nucleosynthesis



Magnetic Trapping of UCN

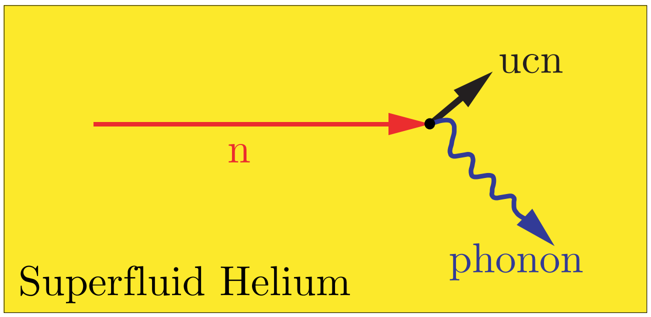


- Produce UCN using superthermal scattering
- Confine UCN with a magnetic trap
- Detect UCN by measuring beta-decay rate as a function of time.

Why Trap?

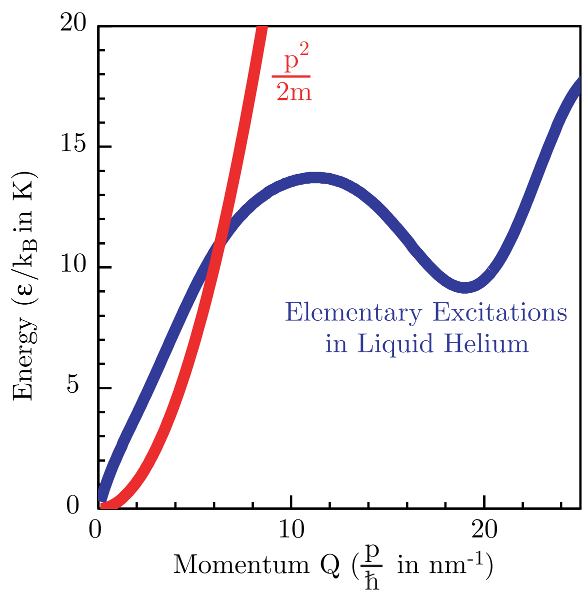
- Long interaction times
- Eliminates systematic effects present in previous experiments

Loading the Trap



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

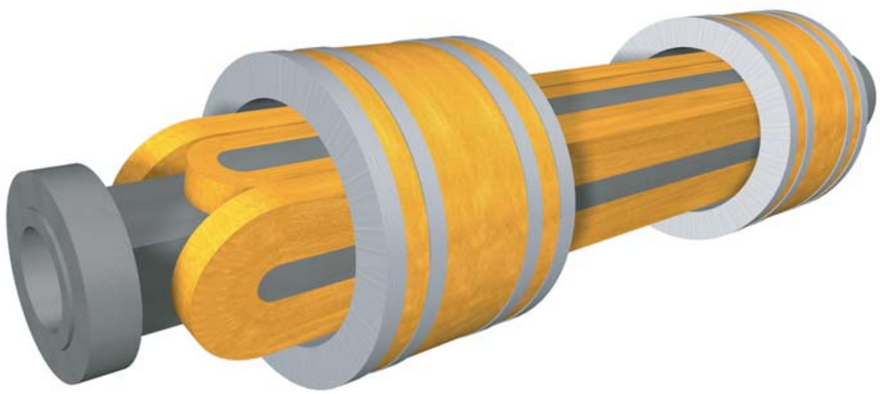
$$E_{ucn} = E_n - E_{phonon}$$

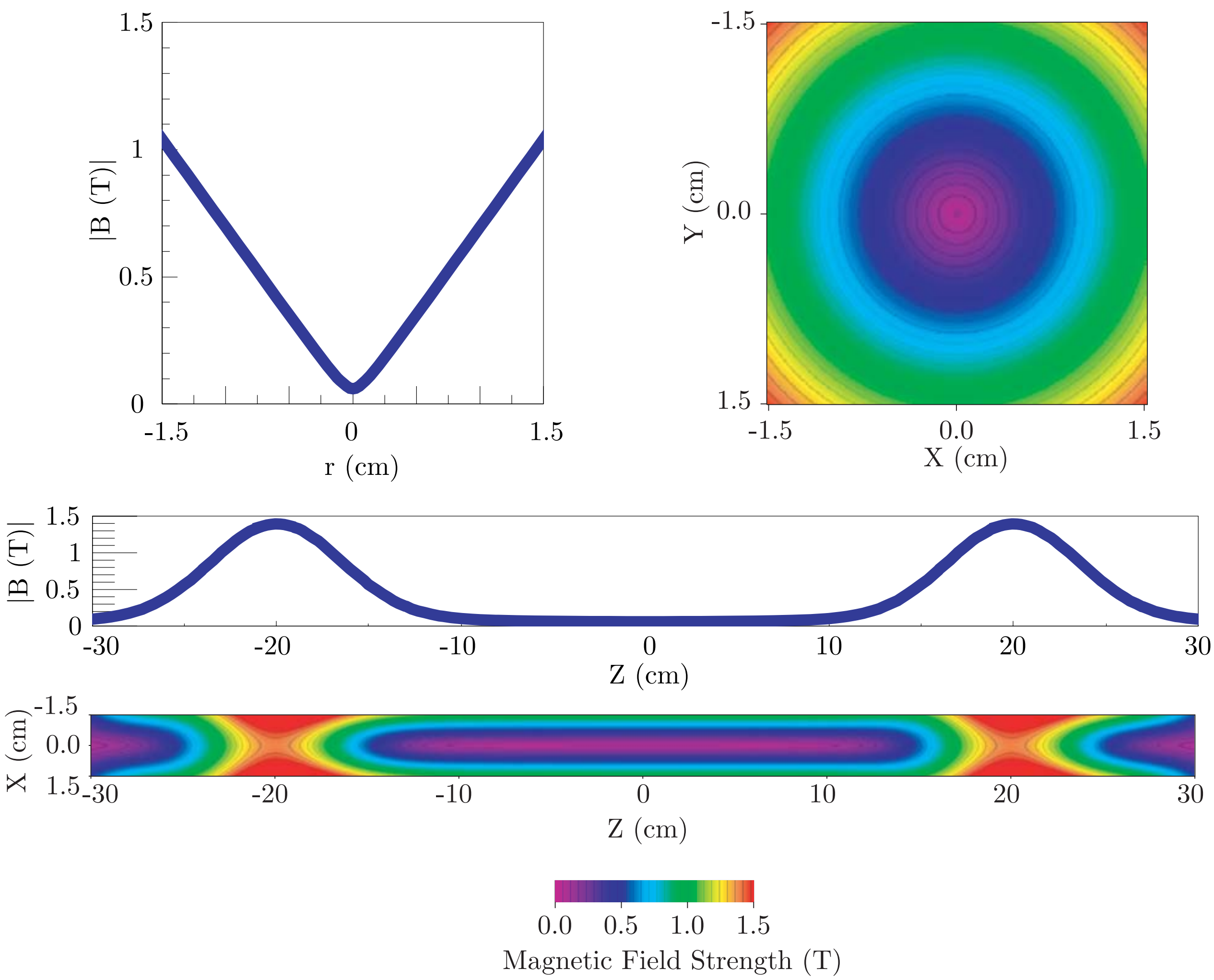


- Neutrons of energy E ≈ 0.95 meV (12 K or 0.89 nm) can scatter in liquid helium to near rest by emission of a single phonon.

- Upscattering (by absorption of a 12 K phonon) µ
  Population of 12 K phonons ~ $e^{-12\ K/T_{bath}}$

Ioffe-Type Magnetic Trap

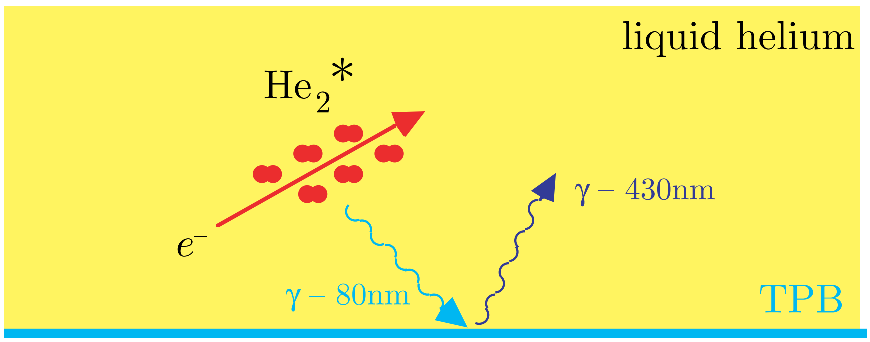




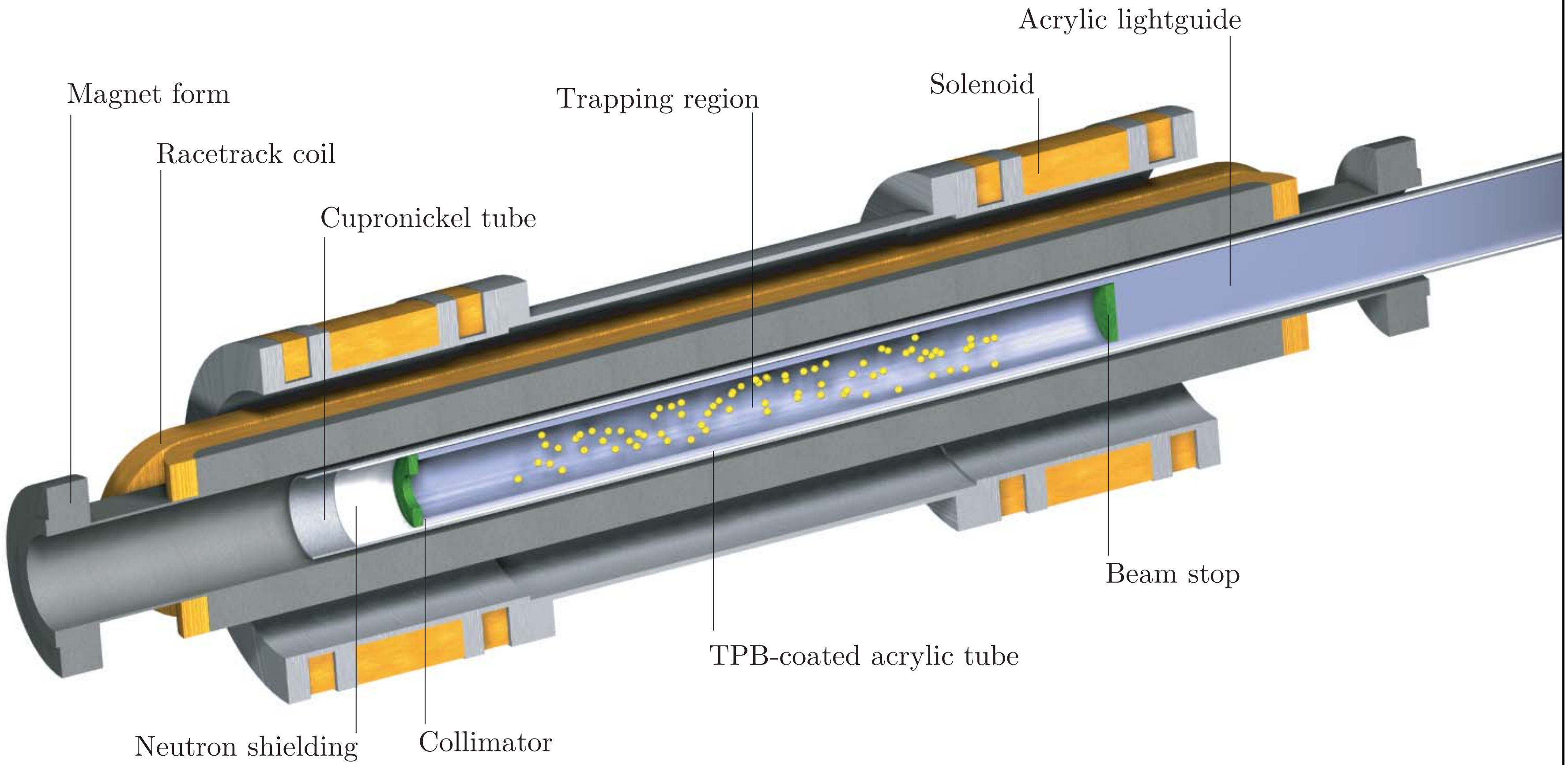
P. R. Huffman

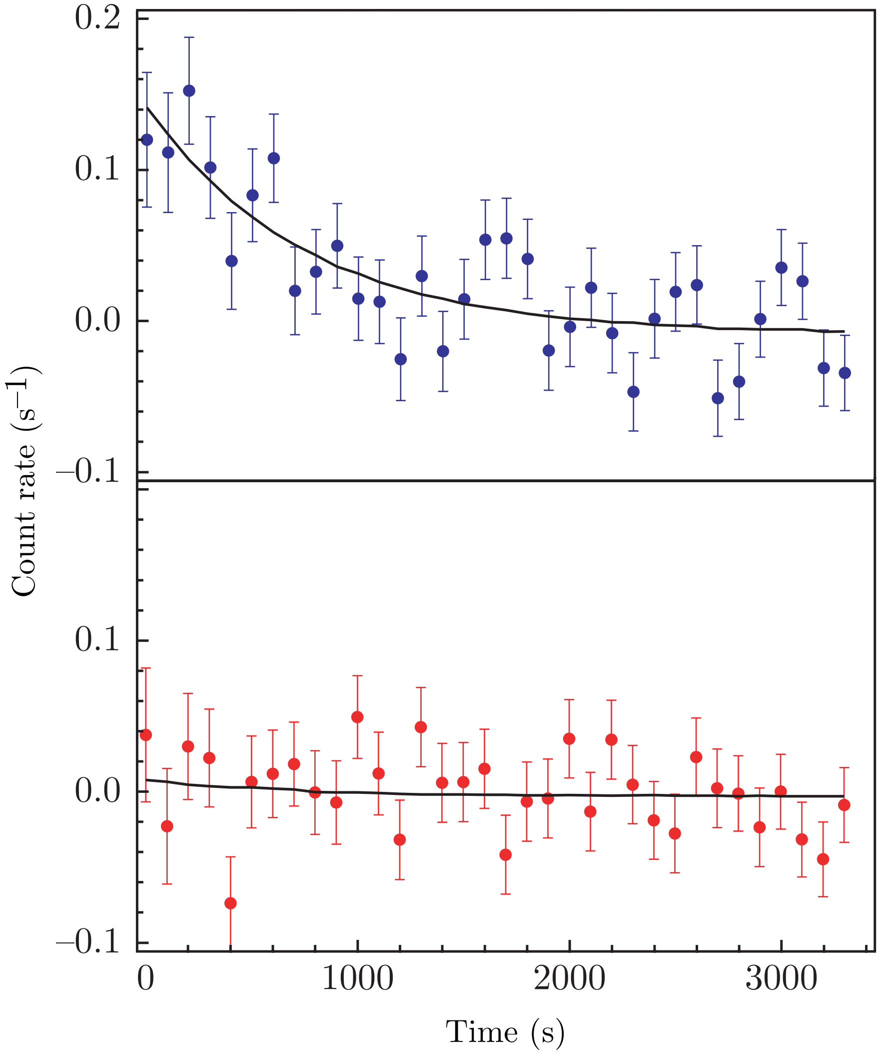
Detection of Trapped Neutrons

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



- 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).


Acrylic lightguide
Magnet form
Trapping region
Solenoid
Racetrack coil
Cupronickel tube
Beam stop
TPB-coated acrylic tube
Neutron shielding
Collimator



$$W_1 = a_1\, e^{-t/\tau} + C_1 \qquad W_2 = a_2\, e^{-t/\tau} + C_2$$

Trapping data (blue):

- a = 0.16 s^{-1} ± 0.03 s^{-1}
- C = 0.003 ± 0.007
- τ = 660 s +290 s/–170 s

^{3}He data (red):

- a = –0.040 s^{-1} ± 0.045 s^{-1}
- C = –0.011 ± 0.011
- τ = fixed at 750 s

Total number trapped:

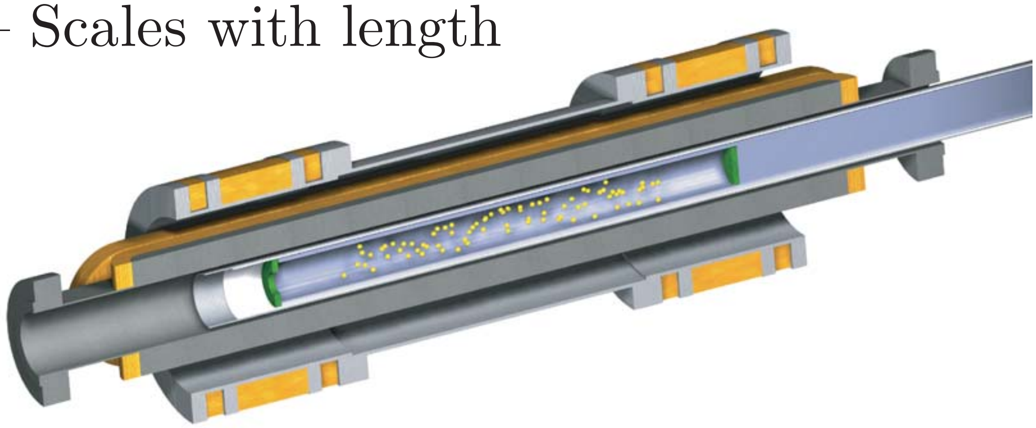
- N = 453 ± 100

Theory Predicts:

- N = 500 ± 170

New Apparatus: GOALS

- Increase the number of trapped neutrons by building a larger, deeper magnetic trap that would fit into our existing dewar. Number trapped:
  - Scales with magnetic field as $B^{3/2}$
  - Scales with the trap radius faster than r^2
  - Scales with length



- Increase the detection efficiency (30 % $\rightarrow >$ 90 %)
  - Clear beam stop, Larger diameter cell

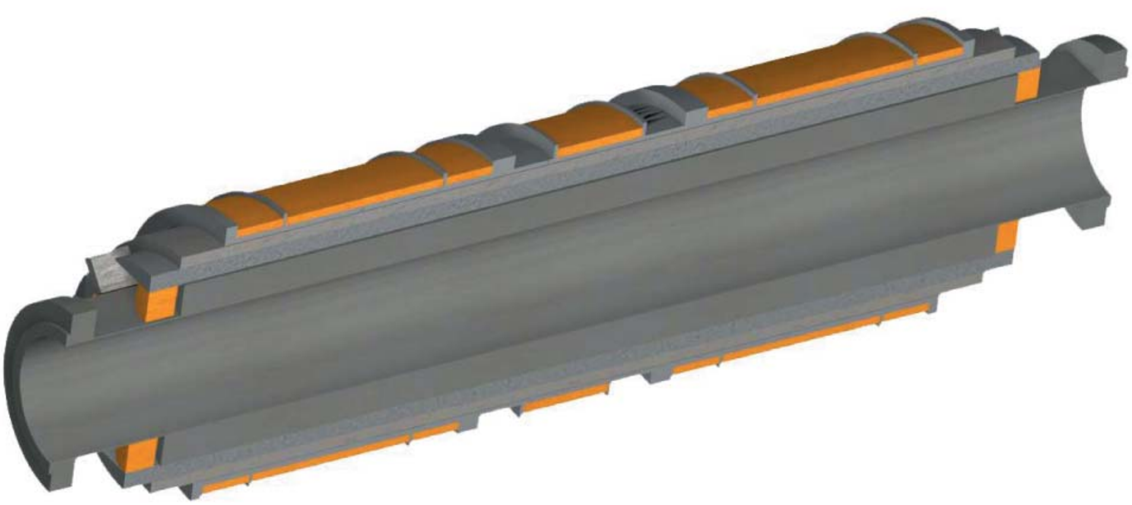
- Reduce backgrounds
  - 0.89 nm neutron monochromator

- Measure the neutron lifetime

Larger, Deeper Magnet

- Original Magnet (demonstration of trapping):
  - $\varnothing_{\text{Magnet}} = 5.1$ cm
  - $\varnothing_{\text{Trap}} = 3.2$ cm, L $= 30$ cm
  - $B_{\text{Trap}} = 1.0$ T, $I_{\text{Trap}} = 180$ A

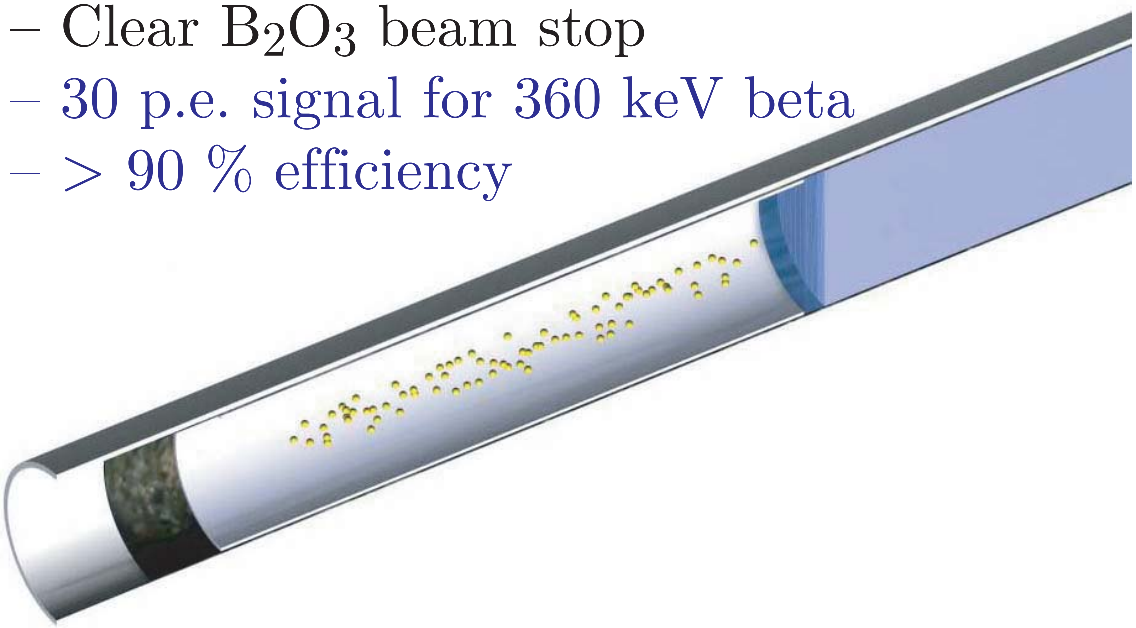
- New Magnet
  - $\varnothing_{\text{Magnet}} = 10.5$ cm
  - $\varnothing_{\text{Trap}} = 8.6$ cm, L $= 27$ cm



Increased Detection Efficiency

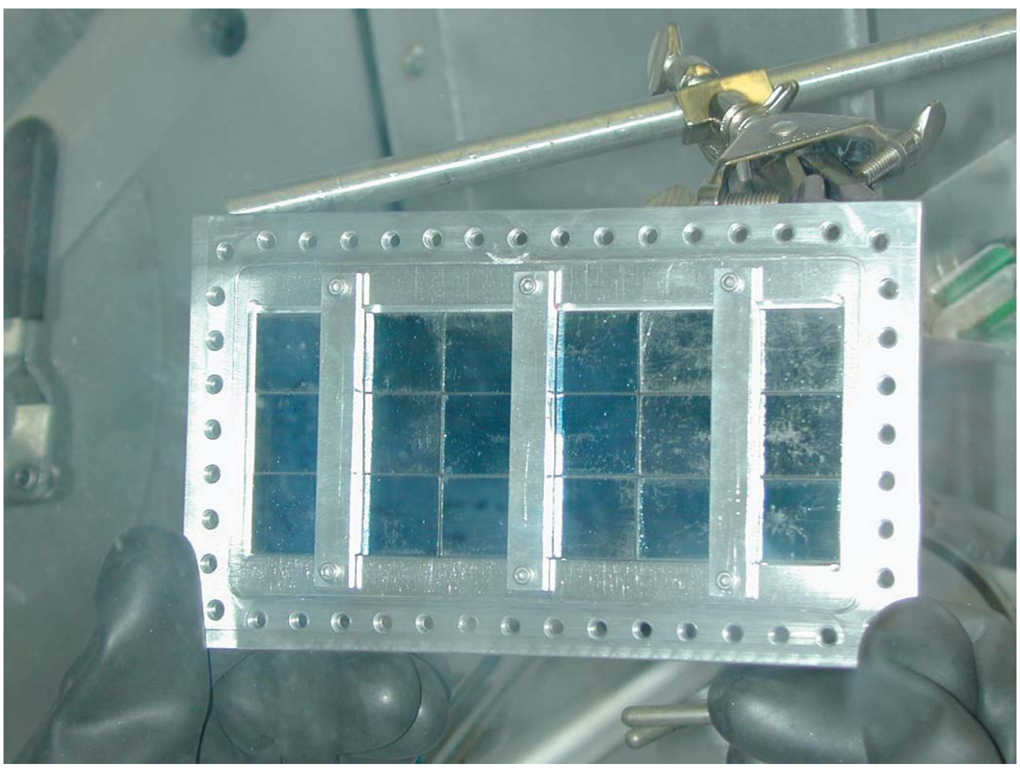
- Original design:
  - TPB in polystyrene
  - Light transport via total internal reflection
  - 5 p.e. signal for 360 keV beta
  - 30 % efficiency

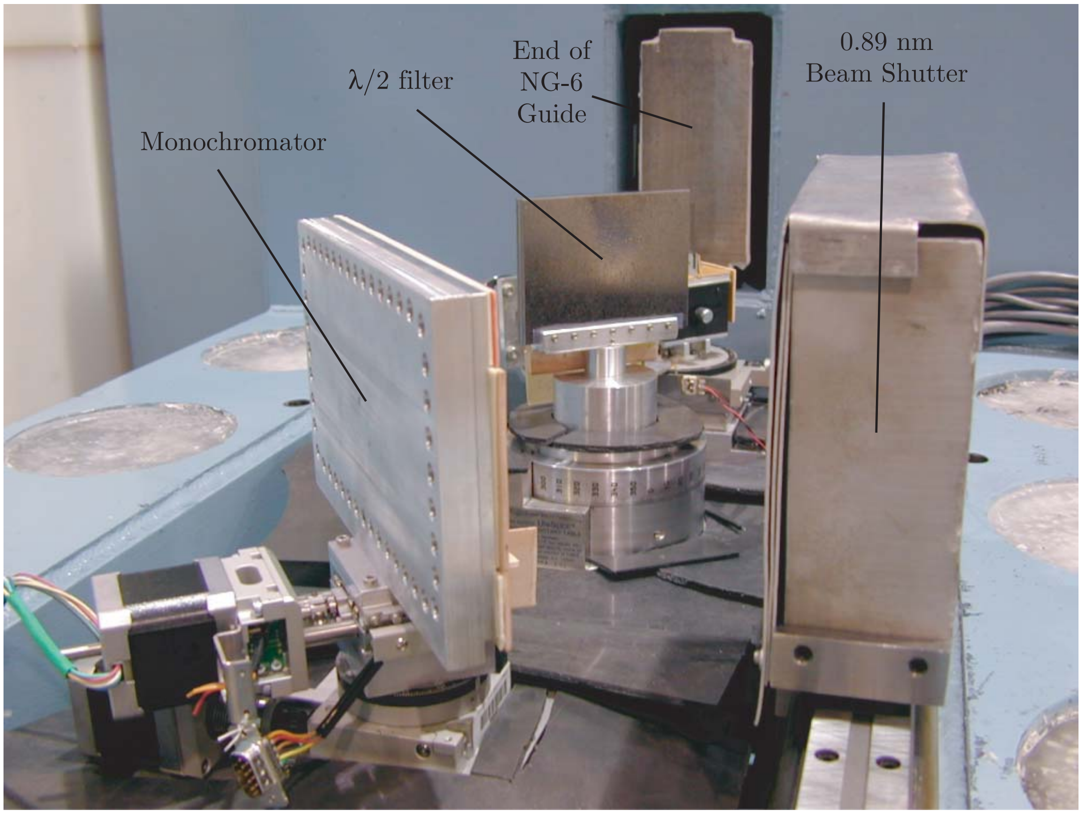
- New design:
  - TPB evaporated onto Gore-tex
  - Clear B_2O_3 beam stop
  - 30 p.e. signal for 360 keV beta
  - $>$ 90 % efficiency

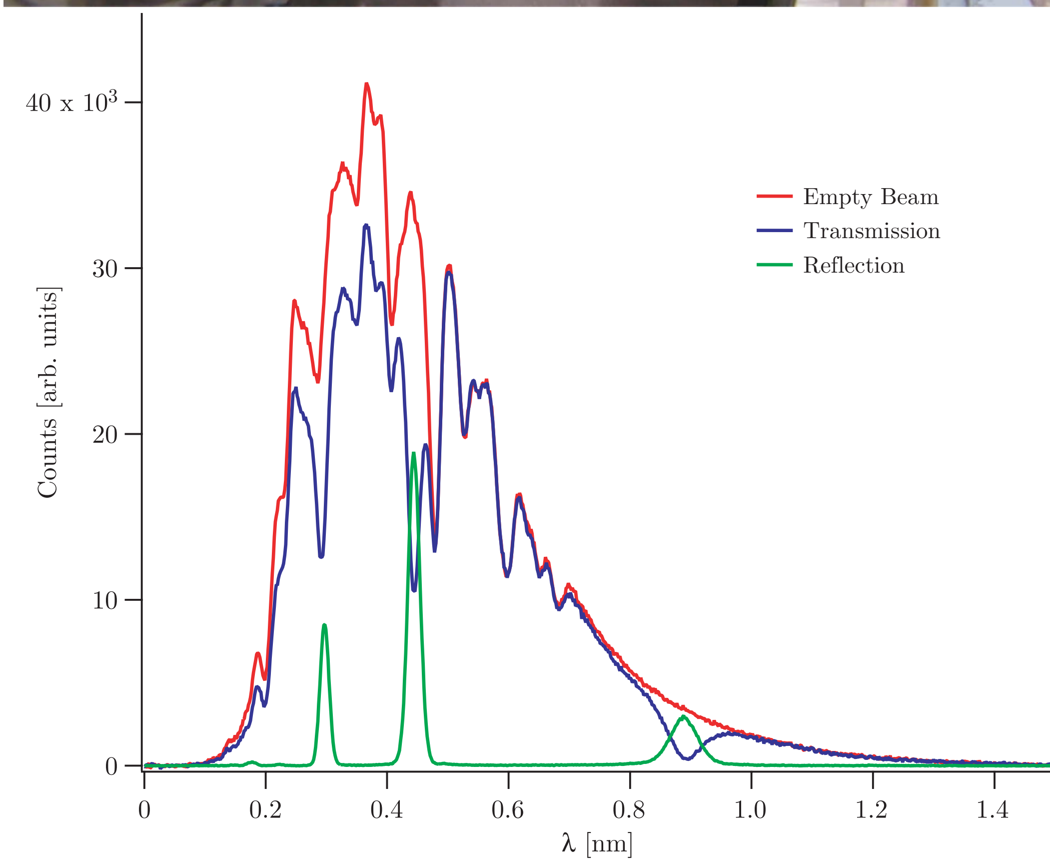


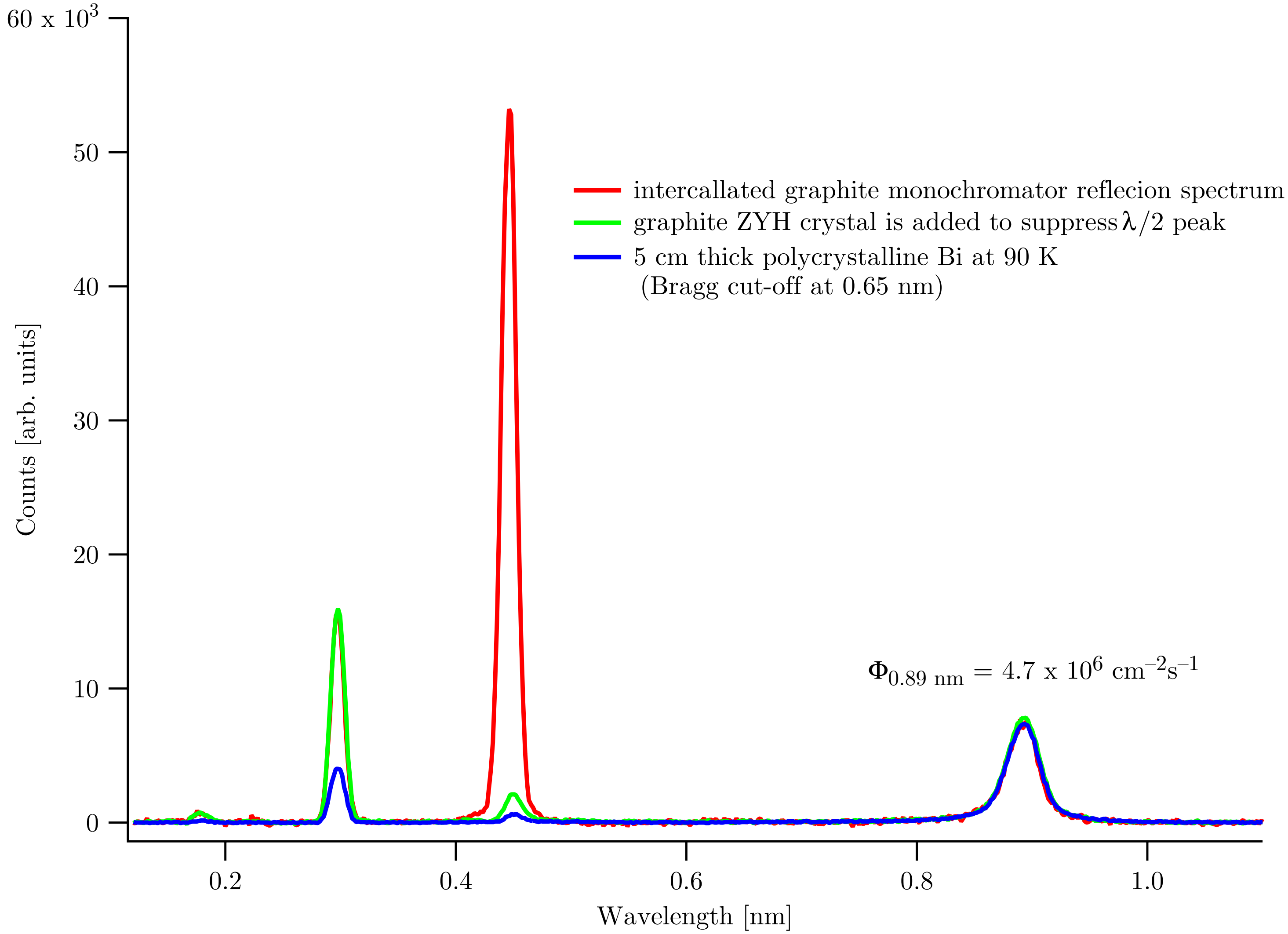
0.89 nm Monochromator

- Stage 2 potassium intercalated graphite
- Consists of 9 tiled pieces (2 cm x 5 cm x 2 mm)
- Mosaics range from 1.1° to 2.1°
- High stage purity




End of
NG-6
Guide
0.89 nm
Beam Shutter
λ/2 filter
Monochromator


40 x 10^3
30
20
10
0
Counts [arb. units]
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
λ [nm]
Empty Beam
Transmission
Reflection



60 x 10^3
50
40
30
20
10
0
Counts [arb. units]
0.2
0.4
0.6
0.8
1.0
Wavelength [nm]
intercallated graphite monochromator reflecion spectrum
graphite ZYH crystal is added to suppress λ/2 peak
5 cm thick polycrystalline Bi at 90 K
(Bragg cut-off at 0.65 nm)
$\Phi_{0.89\ nm}$ = 4.7 x 10^6 $cm^{-2}s^{-1}$

Conclusions

- Magnetic trapping previously demonstrated:
  - 500 UCN trapped per load;
  - Polarized UCN density of 1.8 cm^{-3}.

  (Huffman *et.al.*, Nature **403**, 2000, p. 62)

- Improvements made to allow a measurement of τ_n:
  - Larger, deeper magnetic trap;
  - Monochromatic 0.89 nm beam;
  - New detection system.

- With current apparatus:
  - ~50 x detected trapped UCN (~3 x density);
  - τ_n measurement of ± 1 – 2 s (statistics).

- Present status:
  - Monochromator installed and characterized;
  - Detector characterized;
  - Demonstrated trapping with new setup;
  - Presently cooling apparatus to start taking lifetime data.