Fundamental Physics with HeII UCN Sources: The Neutron Lifetime and Electric Dipole Moment

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Significance

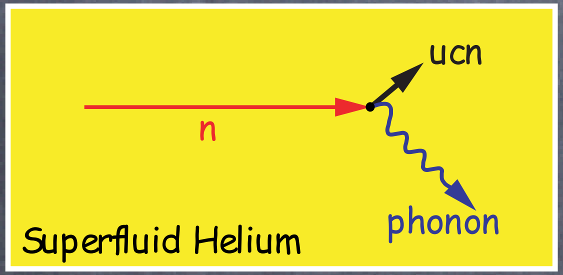
- Neutron Lifetime:
  - Big Bang Nuclosynthesis
  - Unitarity Tests

- Neutron Electric Dipole Moment
  - Tests of the Standard Model
  - Supersymmetry
  - Big Bang Baryogenesis
  - QCD θ parameter

What Do the Experiments Have in Common?

- Use superthemal UCN production in HeII
- Signal detection using charged particle scintillations in HeII

UCN Production in HeII

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

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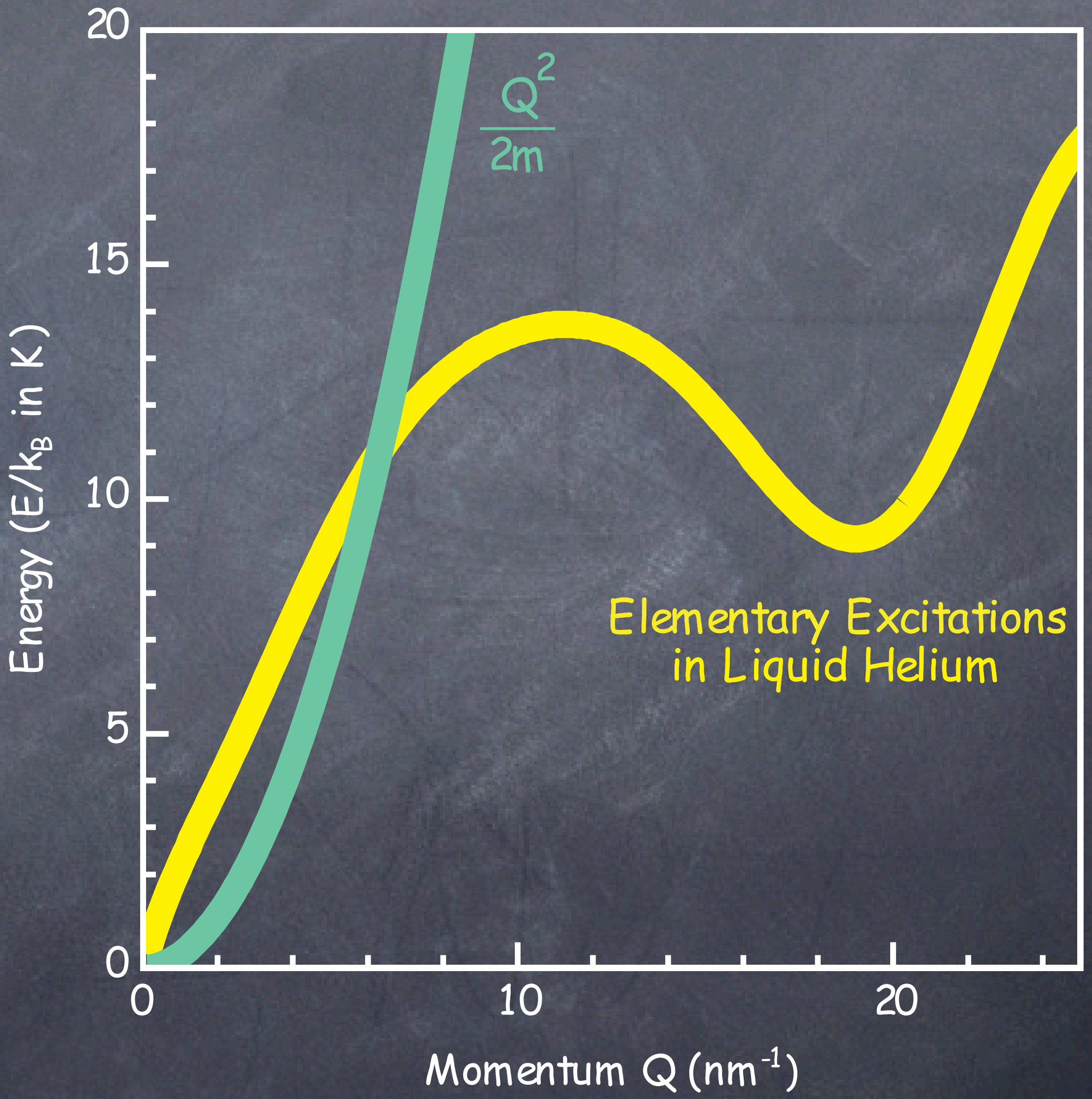
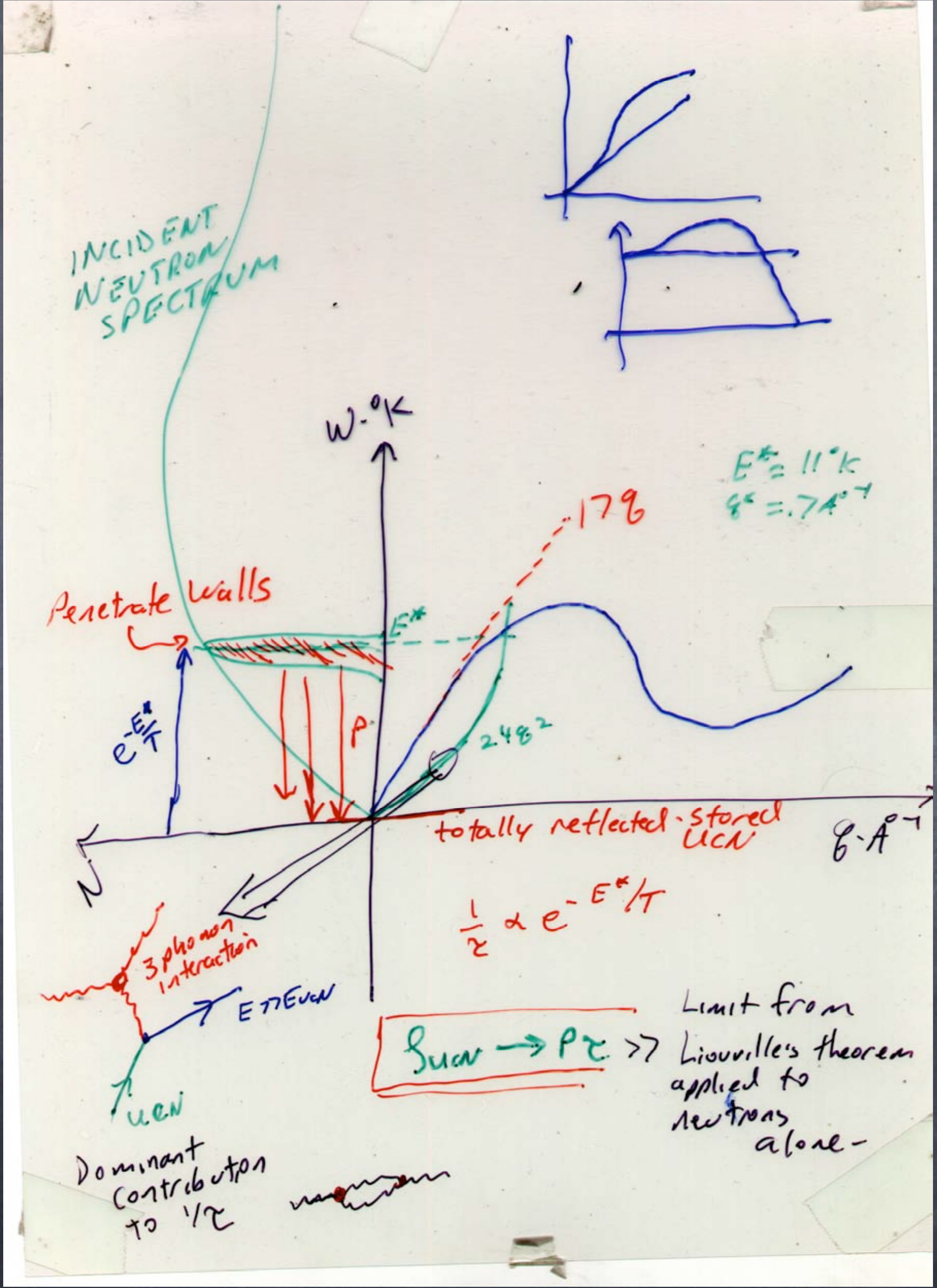
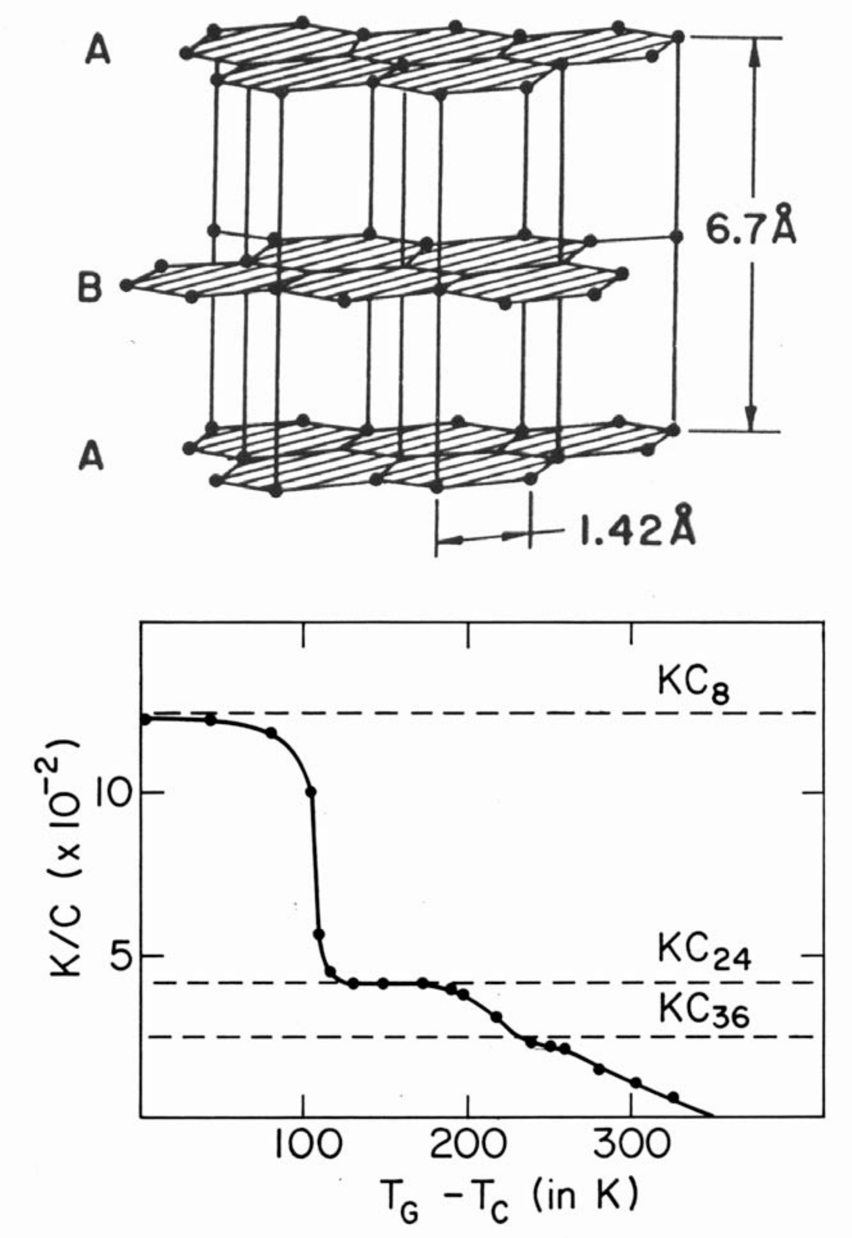
- Upscattering (by absorption of a 12 K phonon)
  ~ Population of 12 K phonons
  ~ $e^{-12\ K/Tbath}$

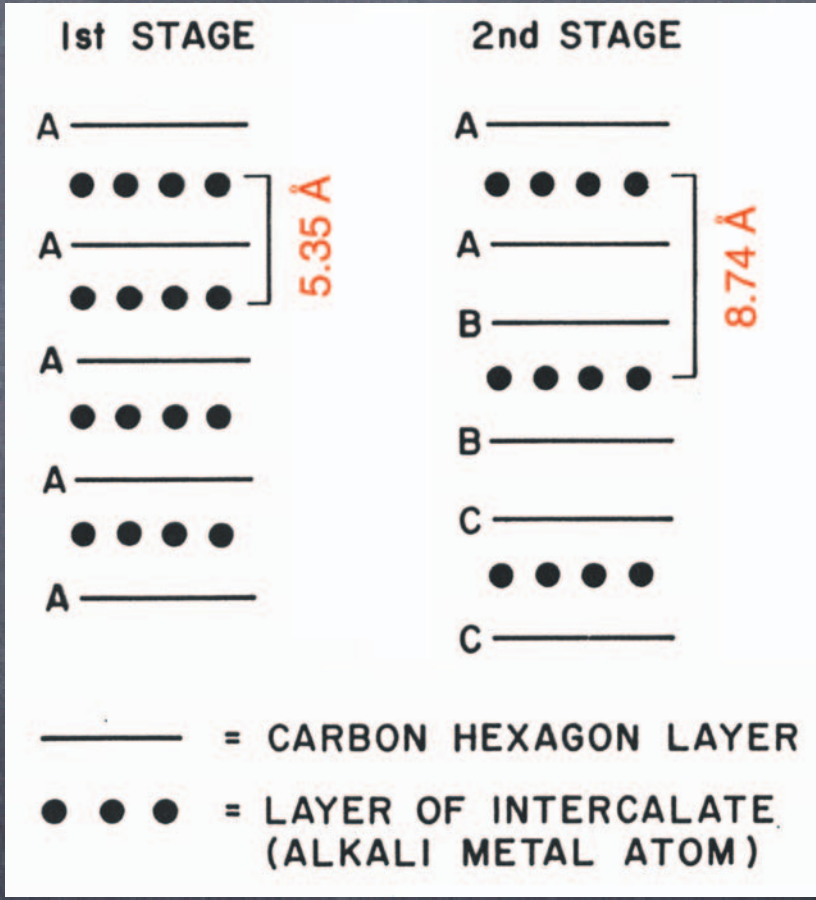




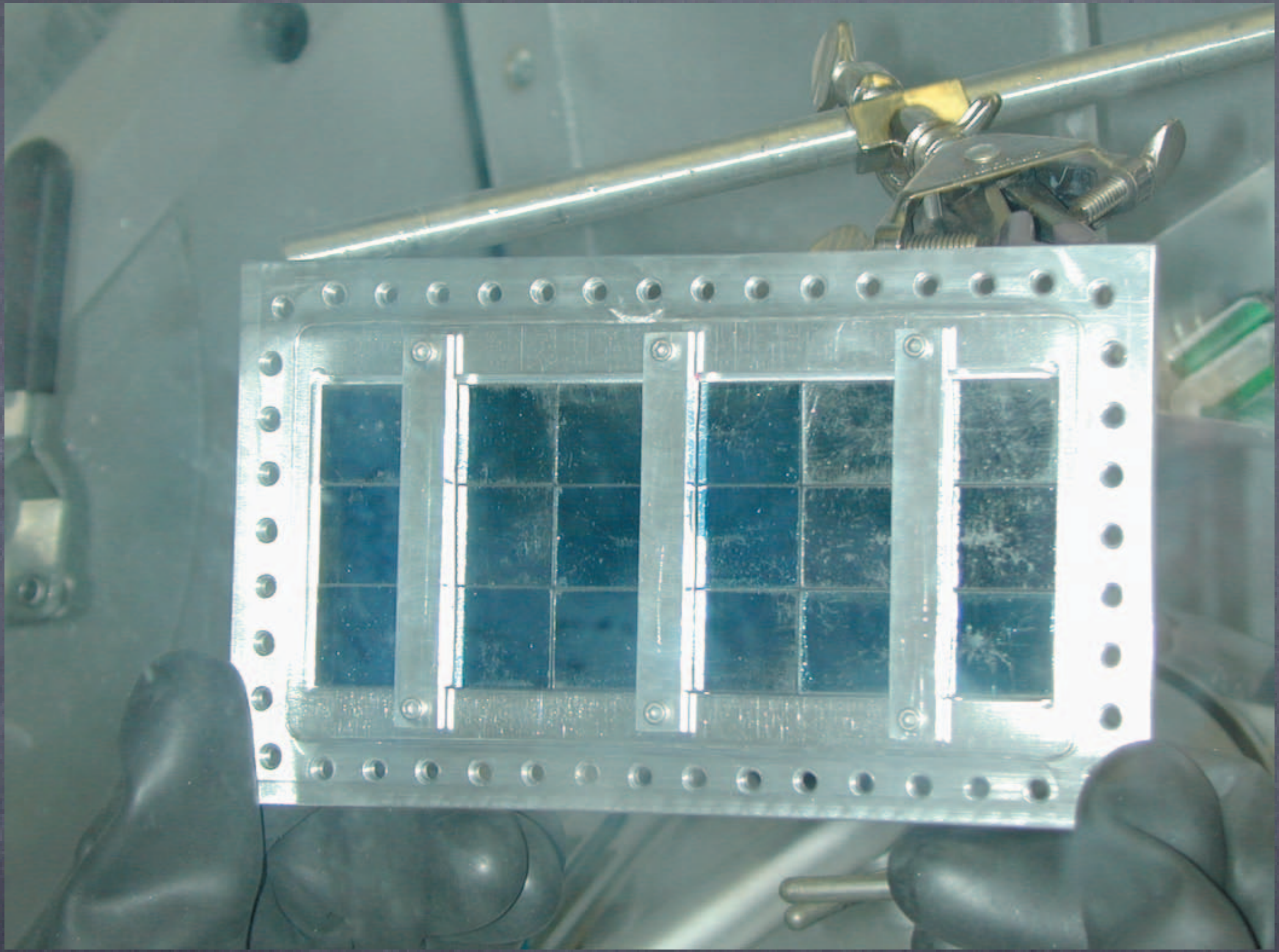
INCIDENT NEUTRON SPECTRUM
W-°K
E* = 11°K
q* = .7Å⁻¹
.17q
Penetrate walls
E*
e^{-E*/T}
P
2.4q²
totally reflected - stored UCN
q-Å⁻¹
N
1/τ ∝ e^{-E*/T}
3 phonon interaction
E ≫ E_UCN
UCN
ρ_UCN → Pτ ≫ Limit from Liouville's theorem applied to neutrons alone-
Dominant contribution to 1/τ

Intercalated Graphite





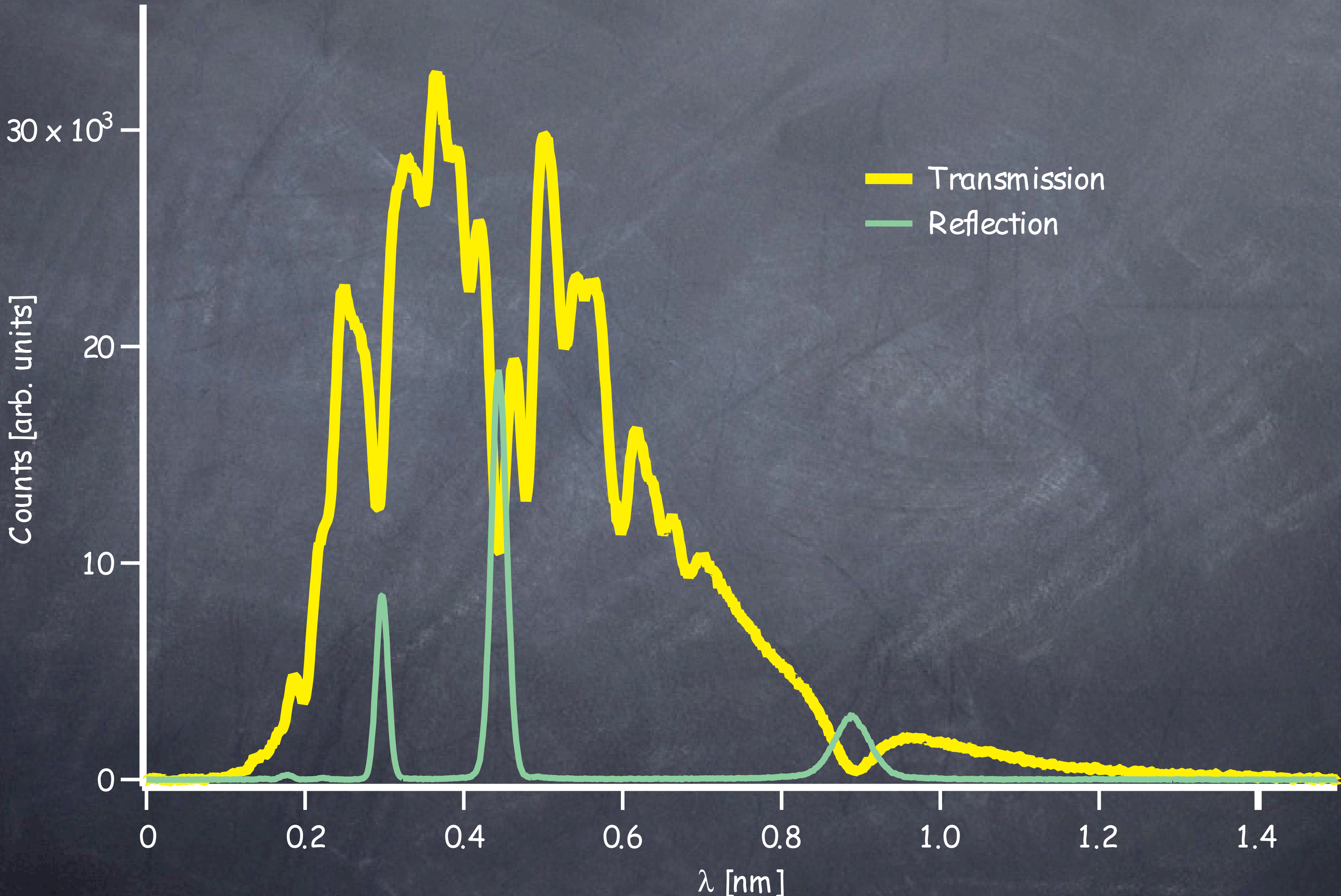
NIST 8.9 Å Monochromator



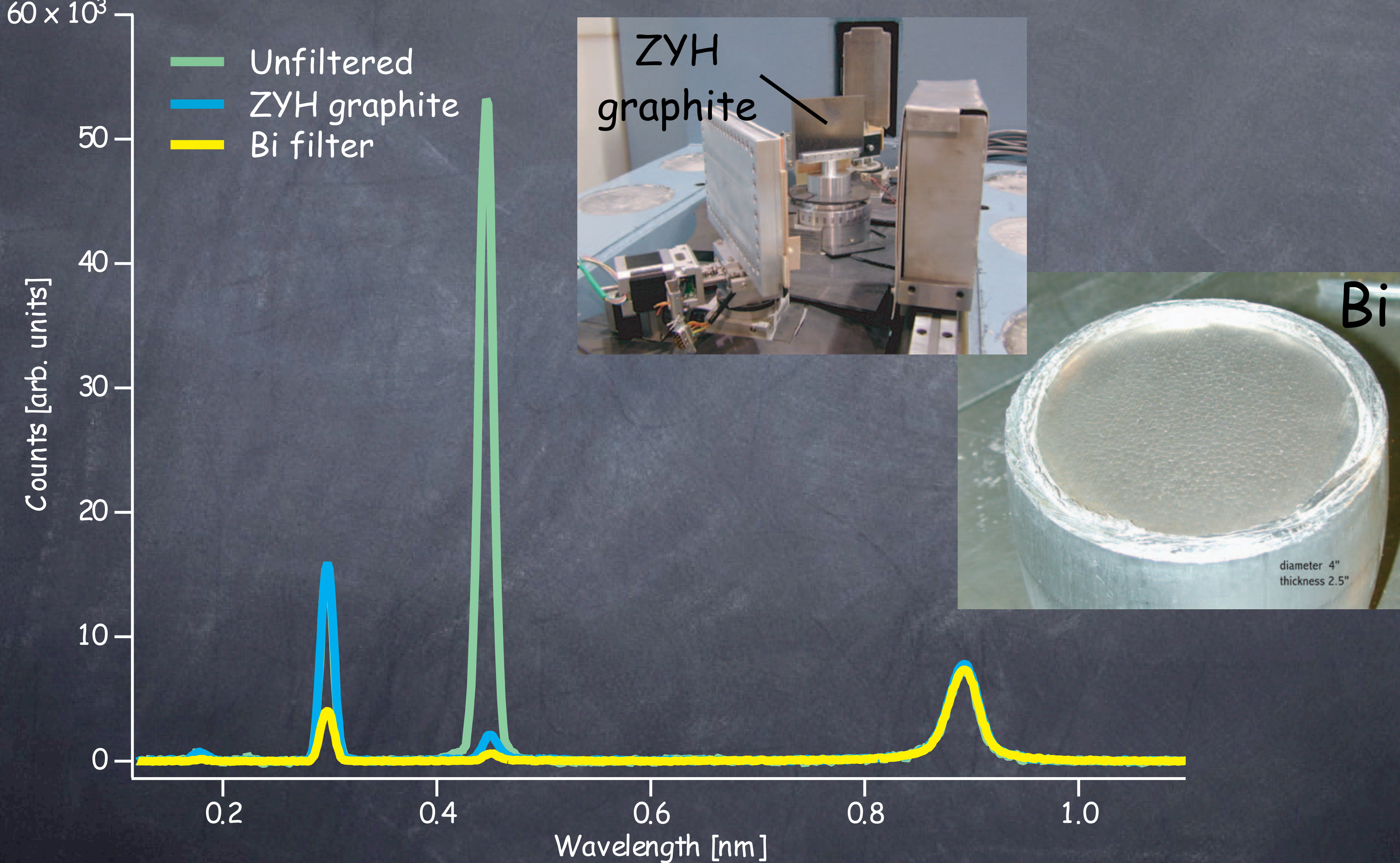
$\Phi = 5 \times 10^6$ n cm^{-2} s^{-1}

85 % reflectivity

Monochromator Spectrum



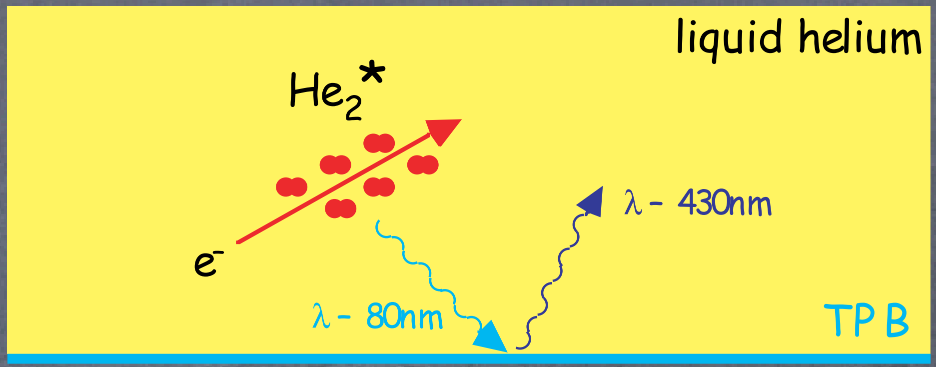
Wavelength Filtering



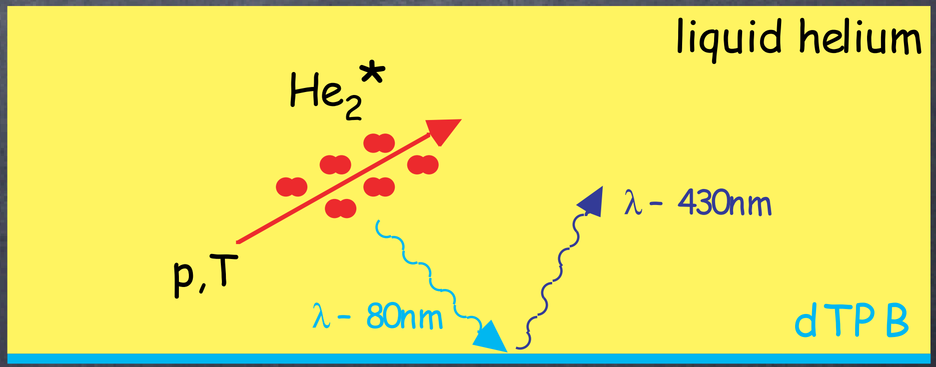
Detection

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

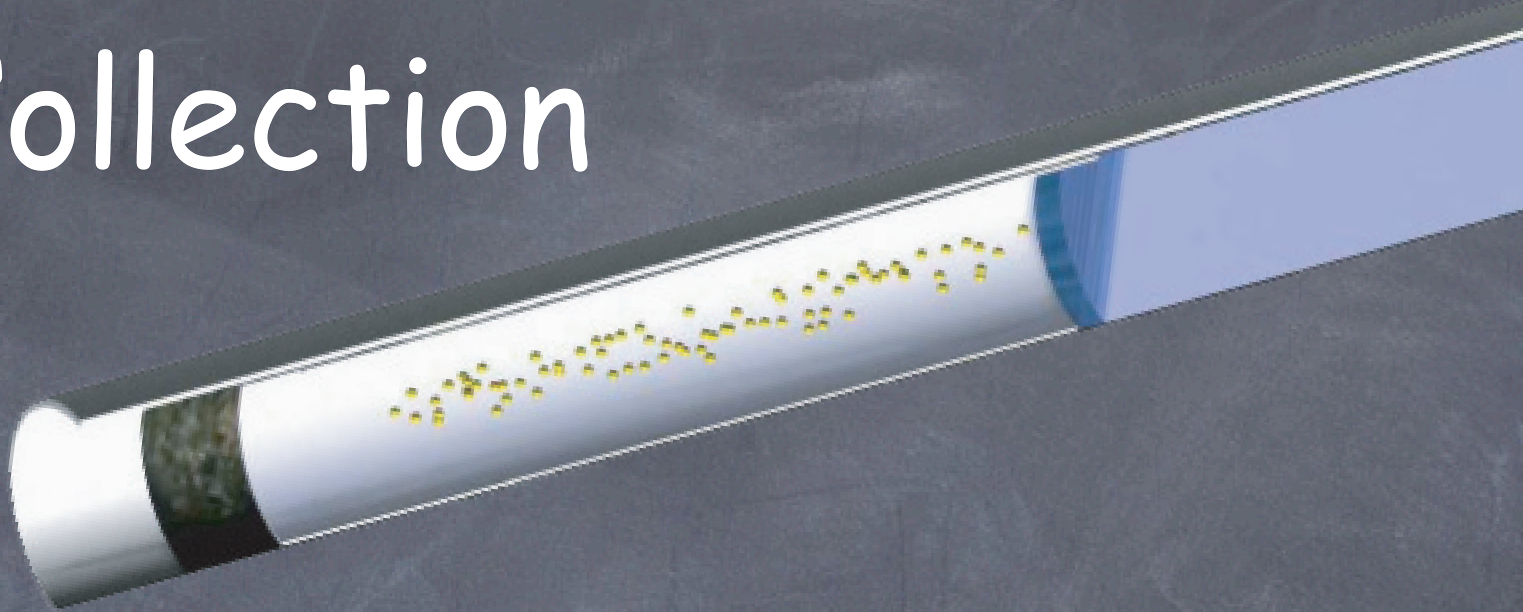
- Recoiling charged particle creates an ionization track in the helium.
- Helium ions form excited He_2^* molecules(ns time scale) in both singlet and triplet states.
- He_2^* singlet molecules decay, producing a large prompt (< 20 ns) emission of extreme ultraviolet (EUV) light.
- EUV light (80 nm) converted to blue using the organic fluor (d)TPB (tetraphenyl butadiene).



$$n + {}^3He \to p + T$$



Light Collection

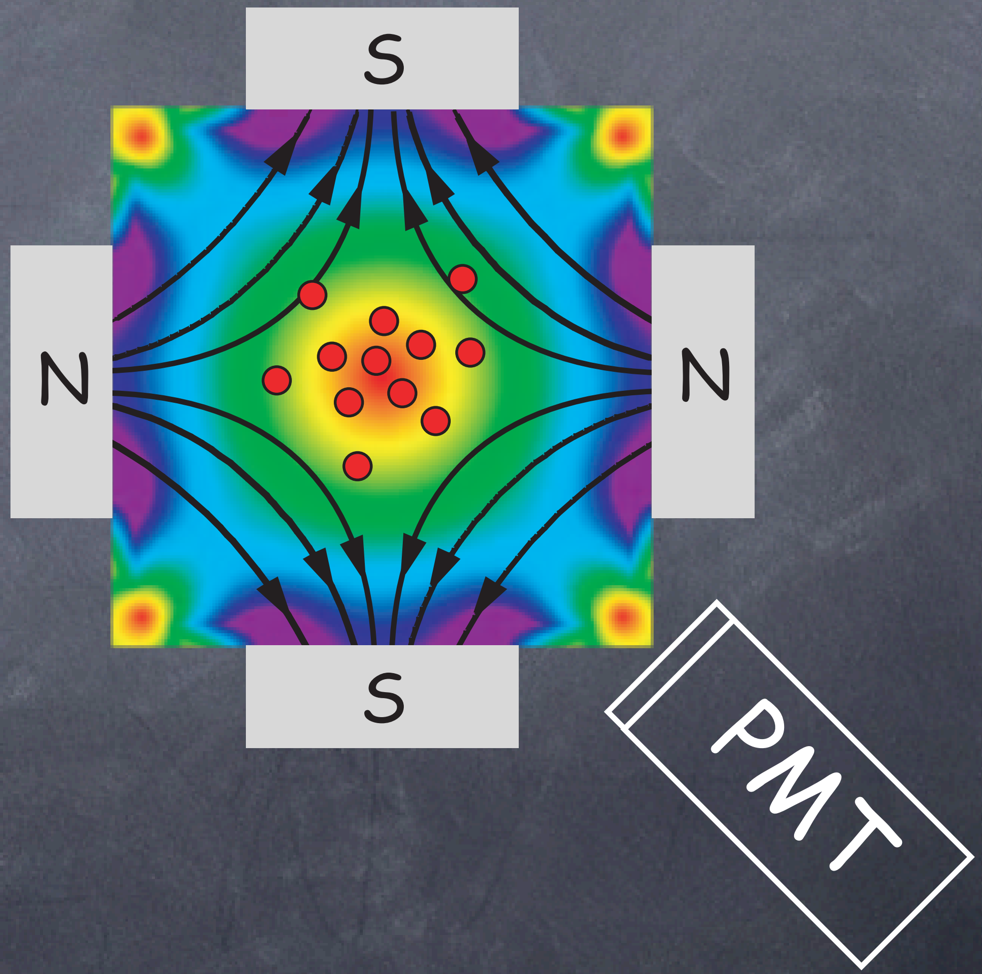


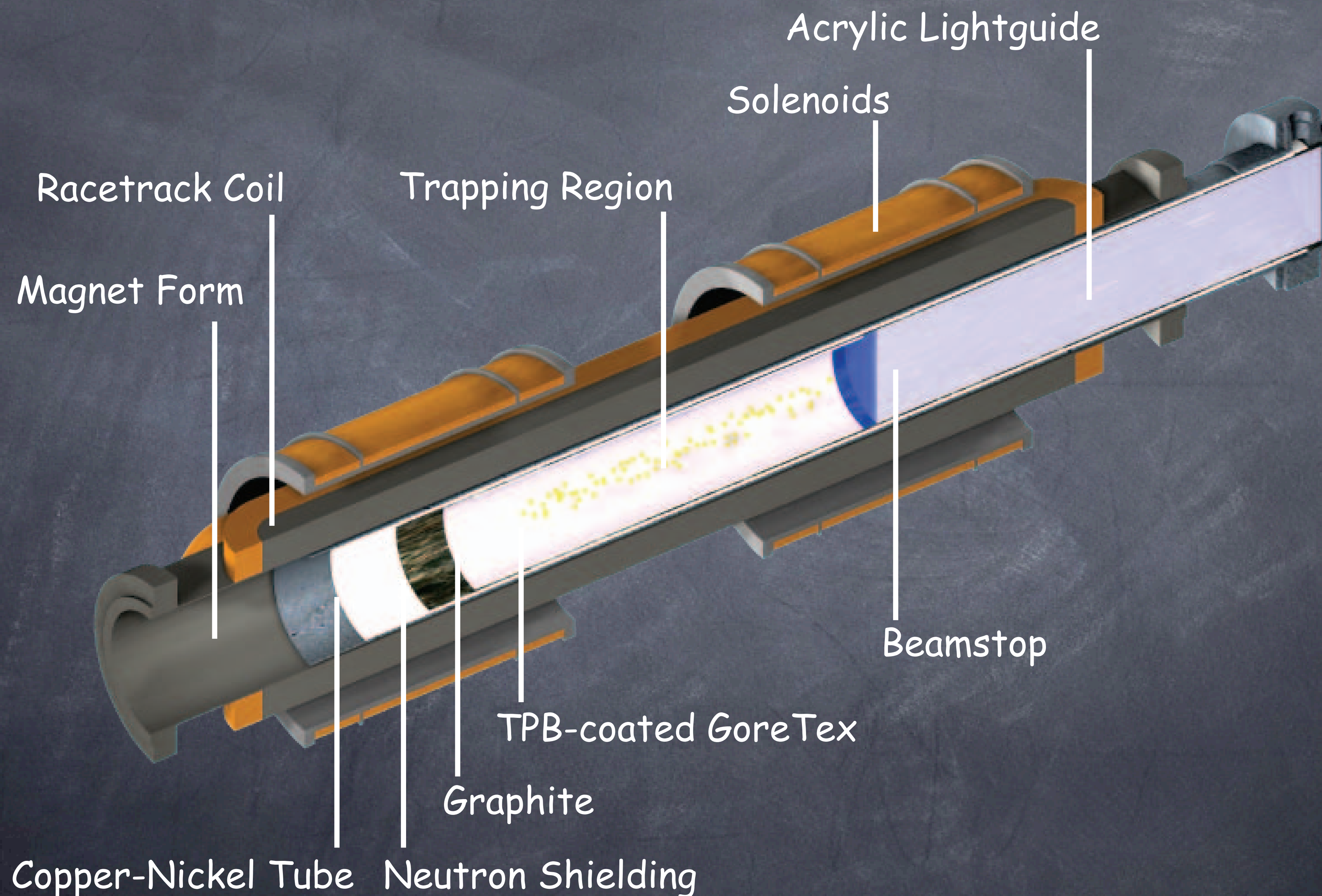
- TPB evaporated onto Gore-tex (lifetime)
  dTPB doped into dPS and coated onto acrylic (EDM)
- Clear B_2O_3 beam stop
- PMTs at room temperature
- 12 p.e. signal for 360 keV beta
  > 90 % efficiency (measured in lifetime experiment)

Determination of the Neutron Lifetime Using Magnetically Trapped UCN

Basic Idea

- Produce UCN using the "superthermal" technique
- Confine low field seekers within a magnetic bottle
- Detect each neutron as it decays using scintillation techniques

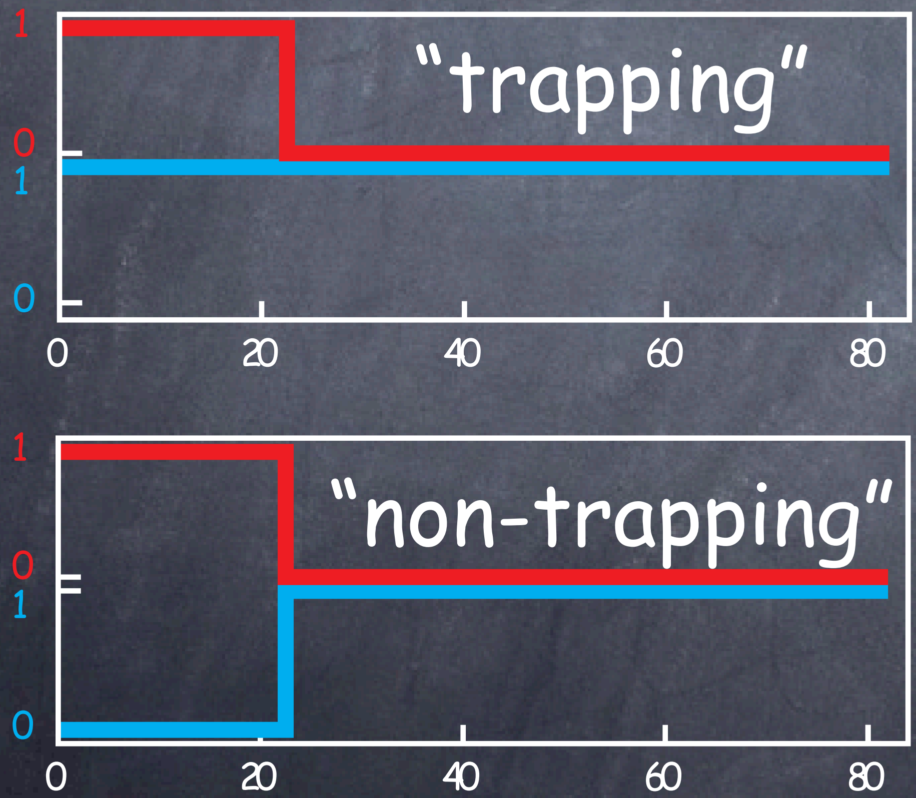




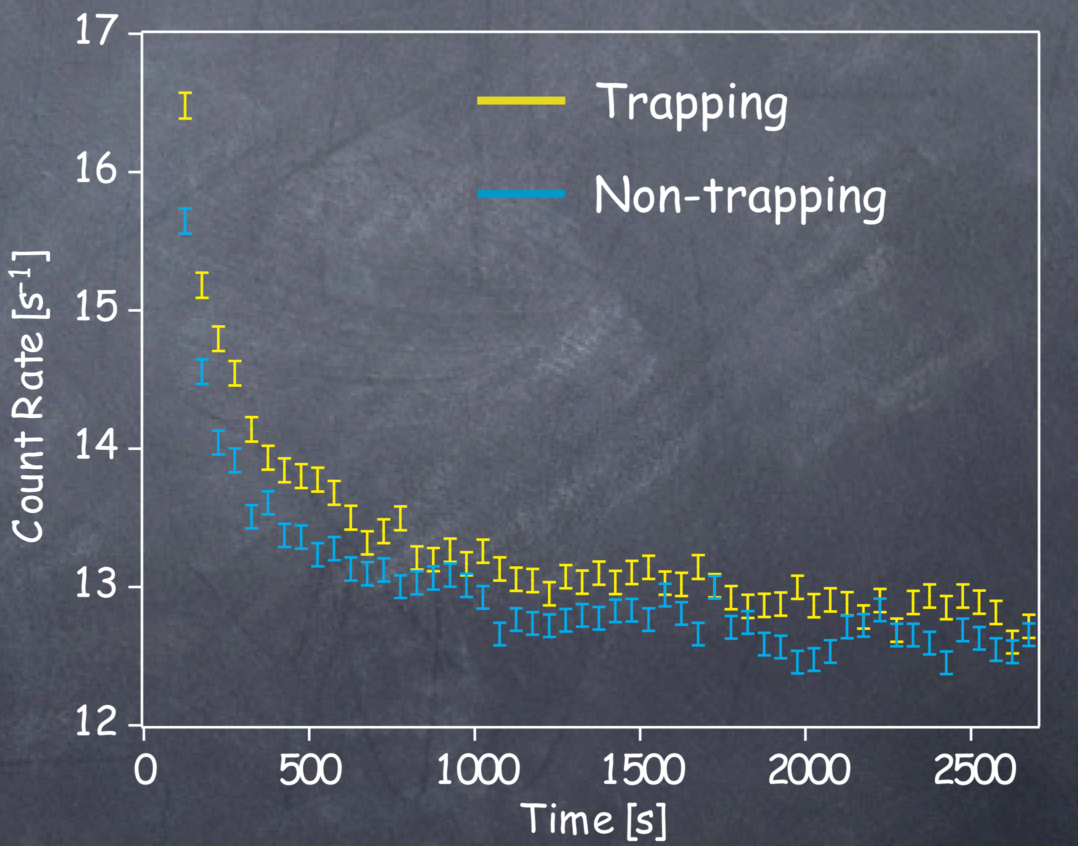
Acrylic Lightguide
Solenoids
Racetrack Coil
Trapping Region
Magnet Form
Beamstop
TPB-coated GoreTex
Graphite
Copper-Nickel Tube
Neutron Shielding

Experimental Method

Experimental Method



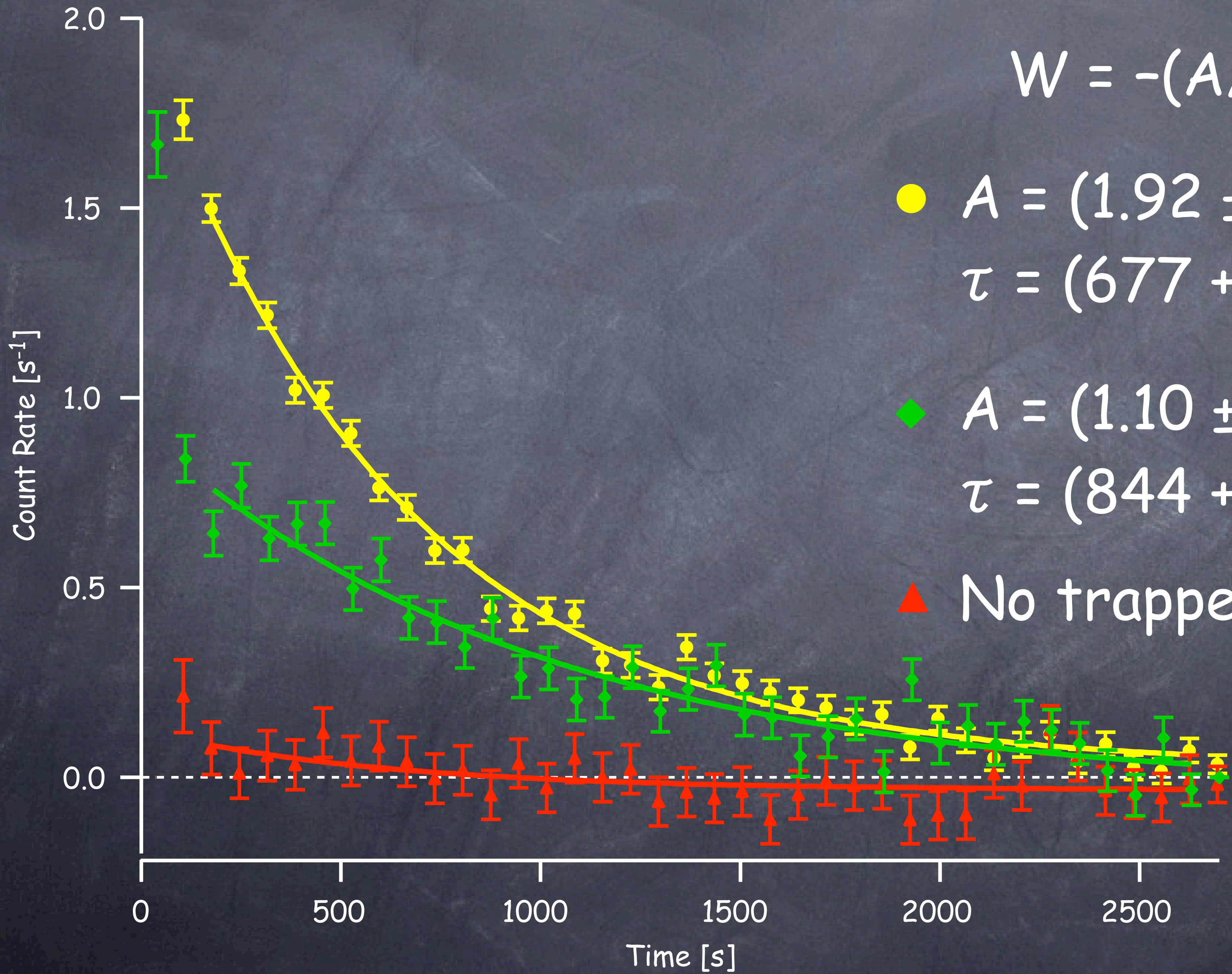
Raw Data



Systematic Effects

- Absorption by ^{3}He– Isotopically pure (10^{-15}) ^{4}He
- Marginal Trapping - field ramping
- Majorana (Spin-Flip) Transitions– no zero-field regions
- Thermal (phonon) Upscattering - T < 250 mK
- Backgrounds - time dependent and time independent

Trapping/Lifetime Data



$$W = -(A/\tau)\, e^{-t/\tau}$$

● $A = (1.92 \pm 0.03)\ s^{-1}$
$\tau = (677\ {+13}/{-12})\ s$

◆ $A = (1.10 \pm 0.06)\ s^{-1}$
$\tau = (844\ {+53}/{-47})\ s$

▲ No trapped neutrons

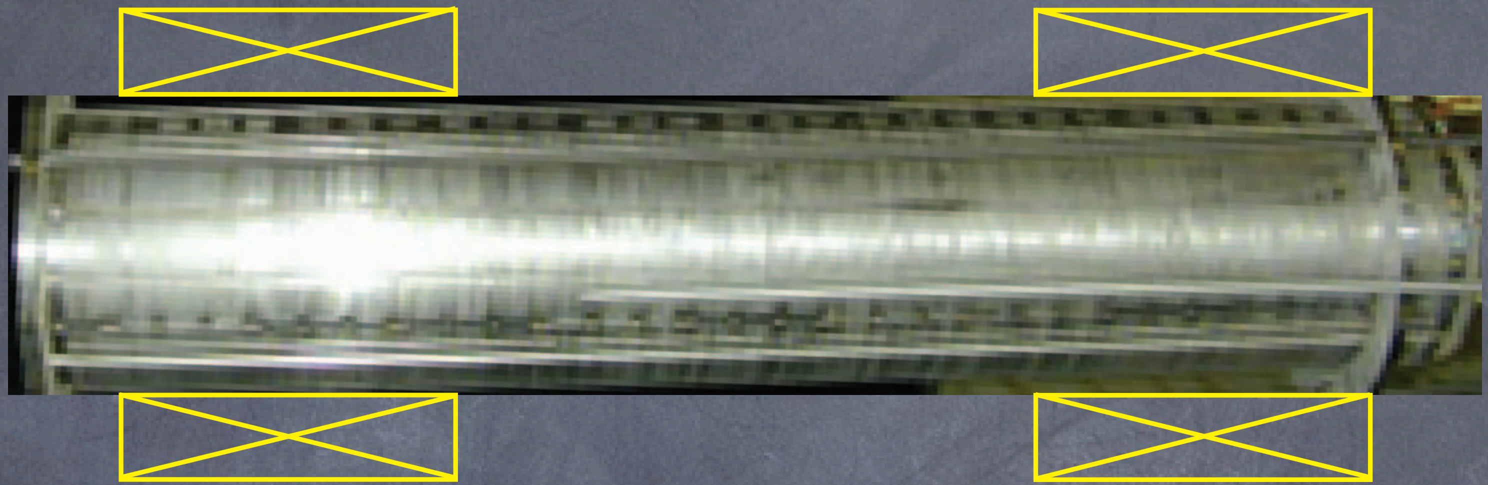
Future Plans

- KEK high-current quadrupole
- Another run @ NIST
- Move experiment to the NCSU UCN source or the Spallation Neutron Source

KEK High-Current Q-pole

- Maximum field is 4.9 T at 4.2K (70 T/m gradient)
- 30 % increase at 1.8 K
- ø = 14 cm, l = 1.14 m
- Have on loan from KEK

Turning the Q-pole into a Trap



- Conservative approach:
  - design 30% under load line
  - axial depth 10% higher than radial depth
- Yields trap with:
  - B = 3.1 T
  - ø = 12 cm, l = 42 cm

Upgrade Estimates

$$\varepsilon_\tau = \frac{d\tau}{\tau} \approx \frac{dS}{S} = \frac{\sqrt{(dT)^2 + (dB)^2}}{S} \approx \frac{\sqrt{2b}}{n} \qquad (b > n)$$

Setup	# trapped	Thresh.	Signal ampl. (s^{-1})	Backgrounds Constant (s^{-1})	Backgrounds Time-dep ampl. (s^{-1})	σ_τ (s) in 40 days	ε_τ = 0.5% (# ofdays)	ε_τ = 0.1% (# ofdays)
1999	500	1.5-1.5	0.175	2.0	4	110		
2001	1200	2-2	0.76	12.5	2.1	55		
2003	3000	3-3	2.0	13.6	2.9	22		
NIST	1650	3-3	1.1	11	2.9	36	>1000	
NIST/KEK	3×10^4	3-3	20	22	5.5	2.9	18	441
SNS/KEK	8.5×10^5	3-3	550	4	150	0.15	<0.1	1.2
NCSU/KEK	1×10^7	3-3	6500	11	<0.1	0.036	<0.1	<0.1

no magnet ramp (1999, 2001, 2003) — magnet ramp (NIST, NIST/KEK, SNS/KEK, NCSU/KEK)

Summary

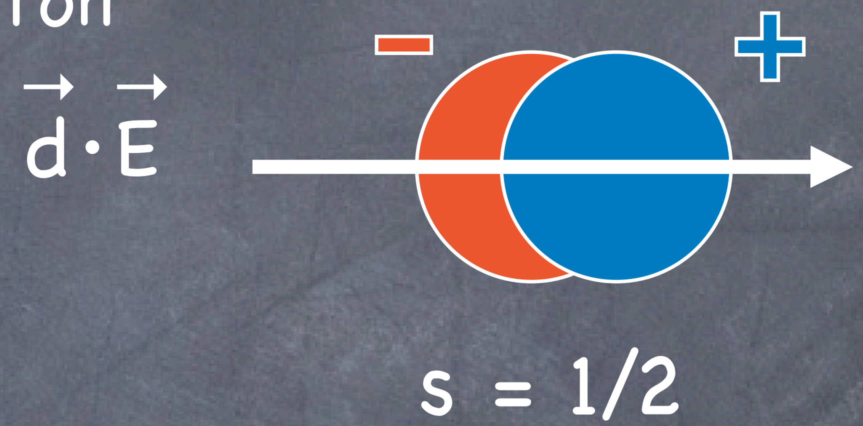
- We can perform a competitive lifetime measurement at NIST with the KEK magnet in the next 3 years.
- Upon a successful outcome, we will move either to the planned NCSU PULSTAR UCN source or to the SNS 0.89 nm beamline to make a significantly improved measurement.

Search for the Electric Dipole Moment of the Neutron

We are developing a new experimental technique to search for the neutron electric dipole moment (EDM) that offers a factor of at least 50 increase in sensitivity over existing experiments when operated at LANSCE and a 500 fold increase at when operated at the SNS.

Neutron EDM

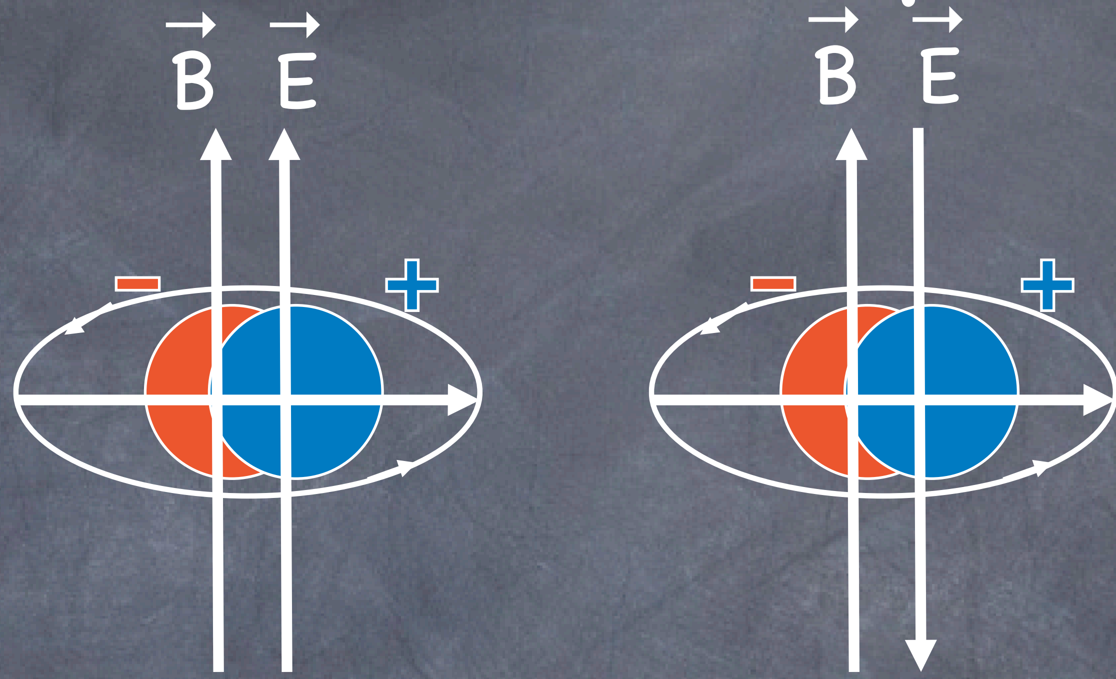
- A permanent EDM $\vec{d}$: separation of the charged constituents of the neutron



- The current experimental technique (ILL) will likely yield $d < 5\times10^{-26}$ e•cm

- We hope to obtain roughly $d < 10^{-28}$ e•cm with UCN stored in superfluid ^{4}He

Basic Technique



- Look for a difference in precession frequency ($f = gB \pm 2dE$) for E parallel and anti-parallel to B
- For $d = 10^{-25}$ e·cm in a 10 kV/cm electric field, we expect a shift in frequency of ≈ 0.5 μHz

Figure of Merit

$$E\sqrt{N\tau}$$

→ x 180 when operated at LANSCE

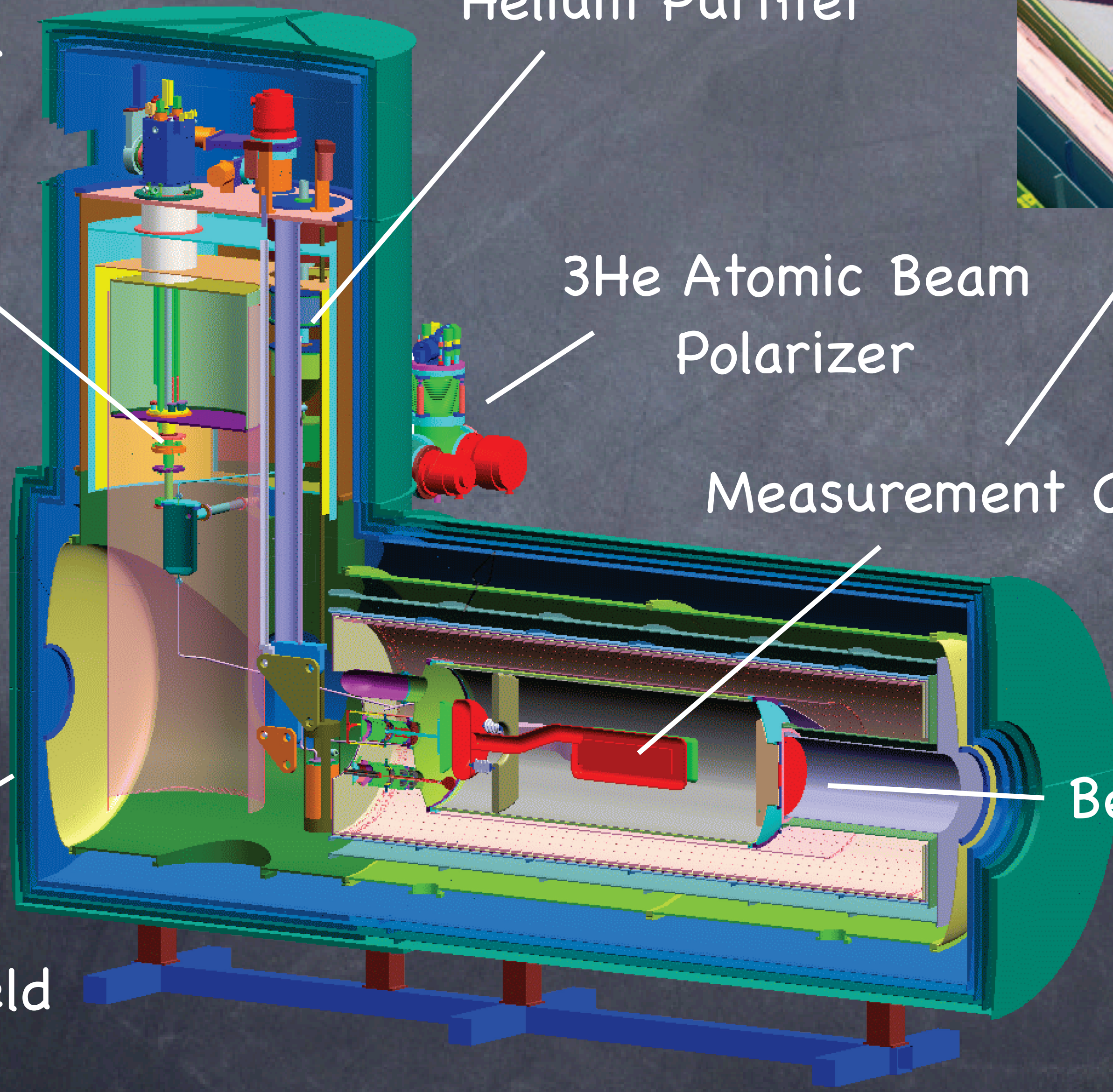
$E \rightarrow 5\,E$

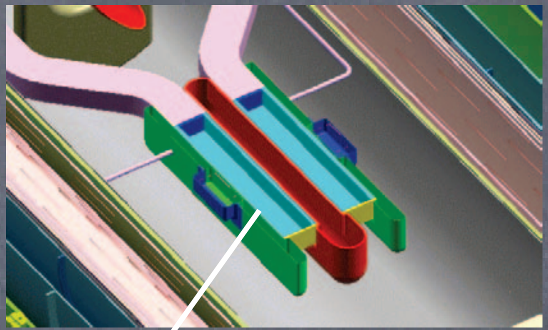
$\tau \rightarrow 5\,\tau$

$N \rightarrow 200\text{-}2000\,N$

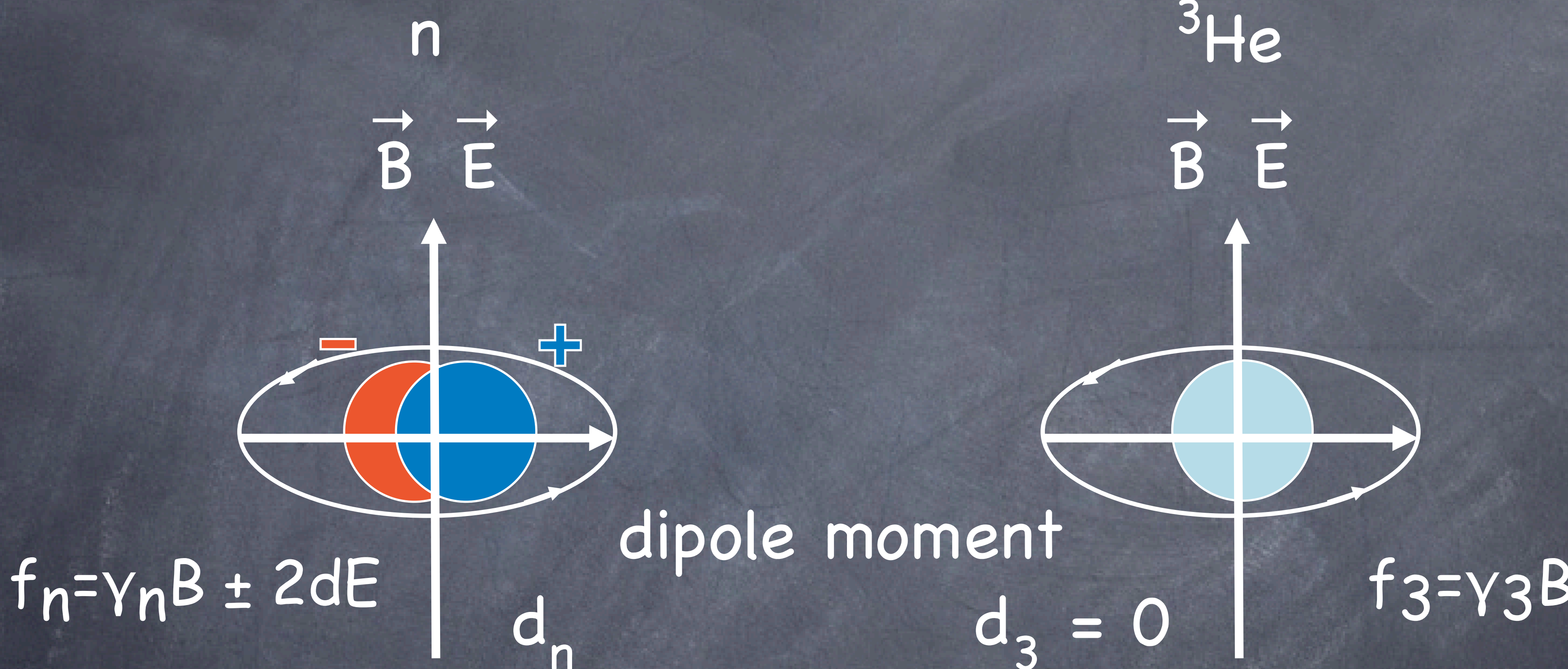
By performing the experiment directly in superfluid helium-4 (dielectric properties + superthermal production) that is doped with polarized helium-3 which serves as a magnetometer and spin precession analyzer

Proposed Experiment





^{3}He Magnetometry



- Look for a difference in precession frequency
  $f_n - f_3 = (\gamma_n - \gamma_3)B \pm 2dE$

^{3}He Magnetometry

$^3He + n \rightarrow t + p$

$\sigma(\text{parallel}) < 10^2$ b $\qquad \sigma(\text{anti-parallel}) \approx 10^4$ b

UCN loss rate:

$1 - p_3 \cdot p_n = 1 - p_3 p_n \cos[(\gamma_n - \gamma_3)B_0 + 2dE]t$

$|\gamma_n - \gamma_3| = |\gamma_n|/10$ – Sensitivity to static magnetic fields is reduced by an order of magnitude!

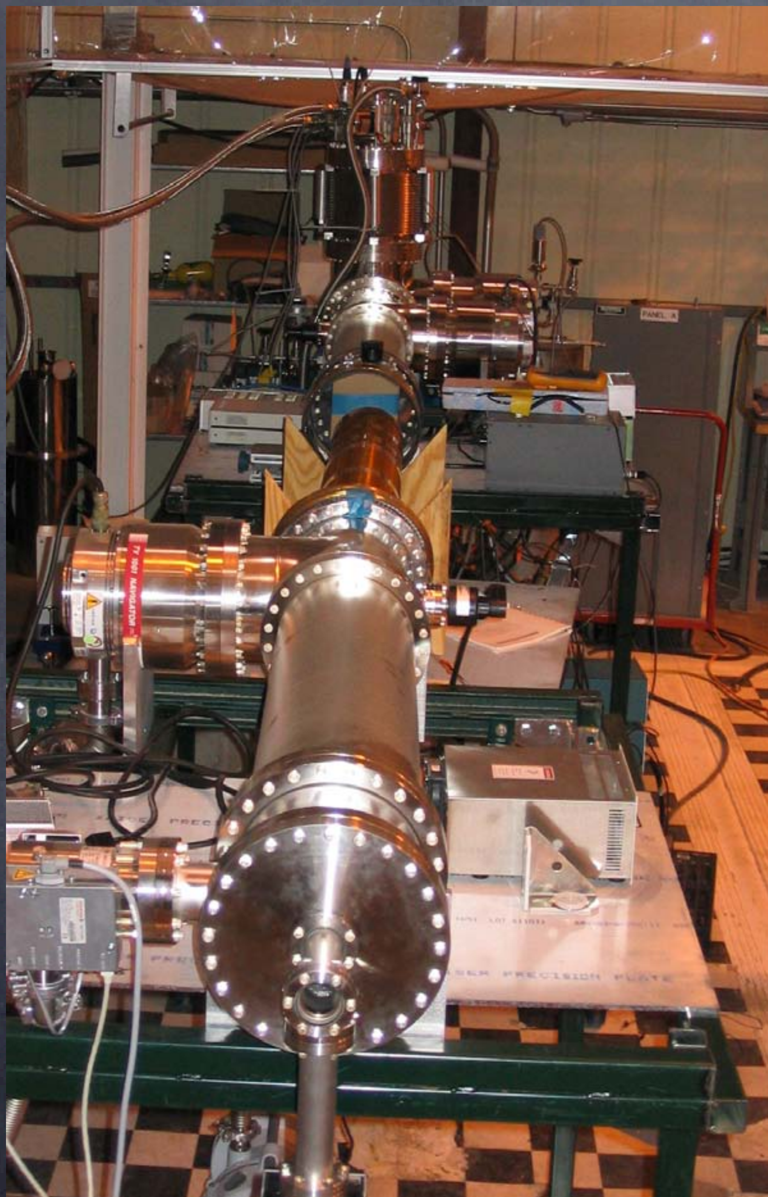
The fractional concentration of ^{3}He must be adjusted to maximize the lifetime τ

$x = \text{Atoms} - {}^3\text{He} / \text{Atoms} - {}^4\text{He} \approx 10^{-10}$

Operation of the Experiment

- Fill cell with superfluid helium, doped with polarized ^3He
- Accumulate UCN for about 1000 s while ramping up HV (superthermal production)
- Flip spins 90° with respect to B_0 by RF pulses
- Observe scintillation signal and SQUID signal as a function of time for 1000 s
- Ramp HV to zero, drain cell of spent ^3He

^{3}He Atomic Beam Polarizer

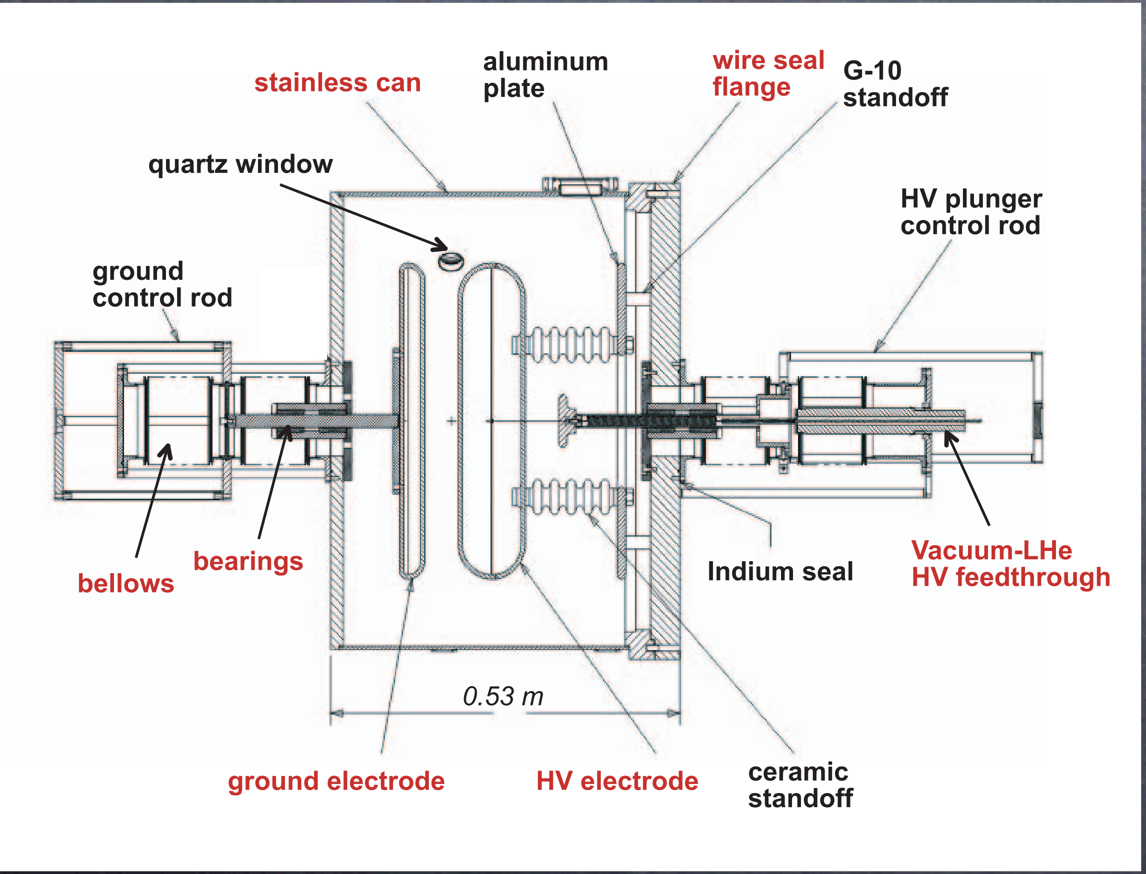


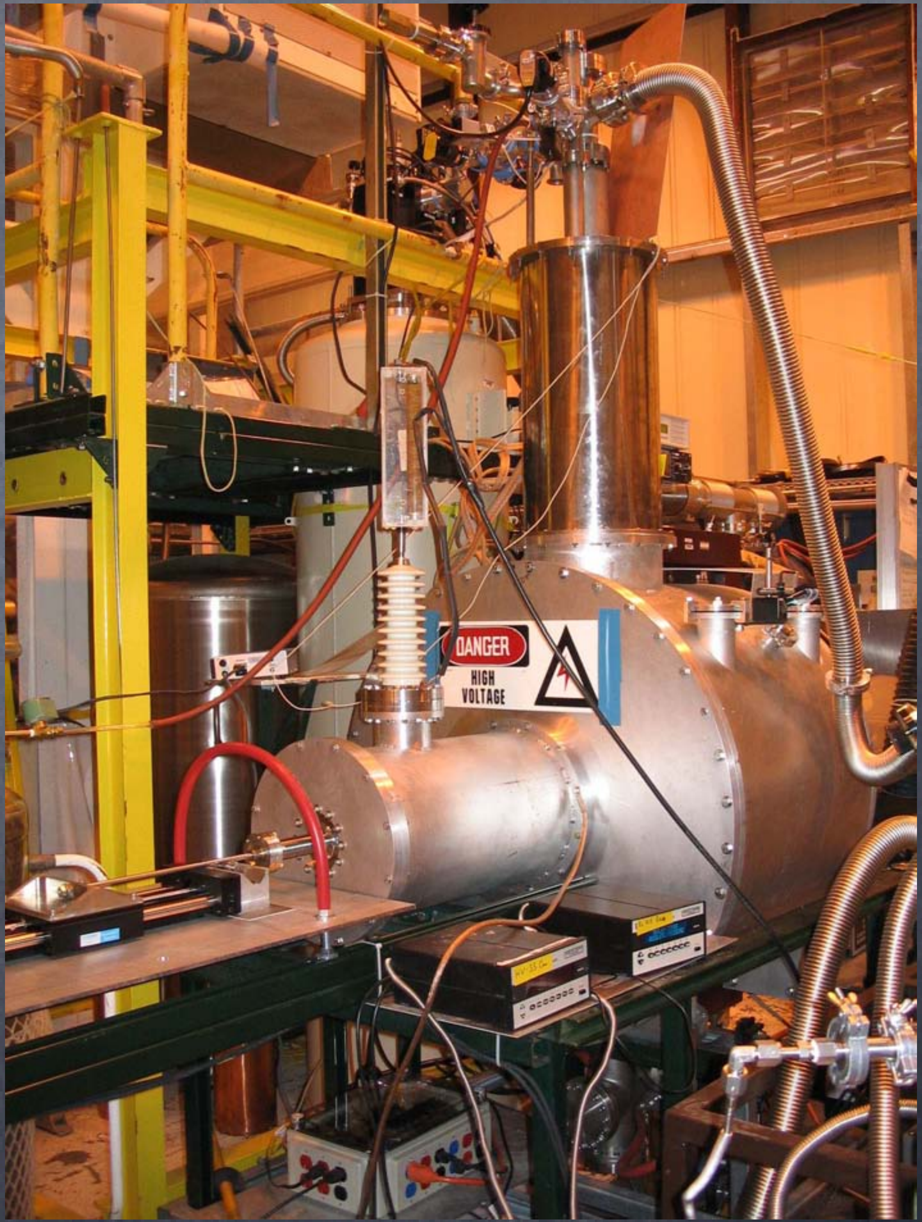
- Final testing is in progress
- Expected flux detected
- Average velocity < 100 m/s
- Polarization measurements are consistent with the 100% expectation
- Differential pump stages will be added soon, final tests will be completed

High Voltage System

Uses a capacitive amplification technique

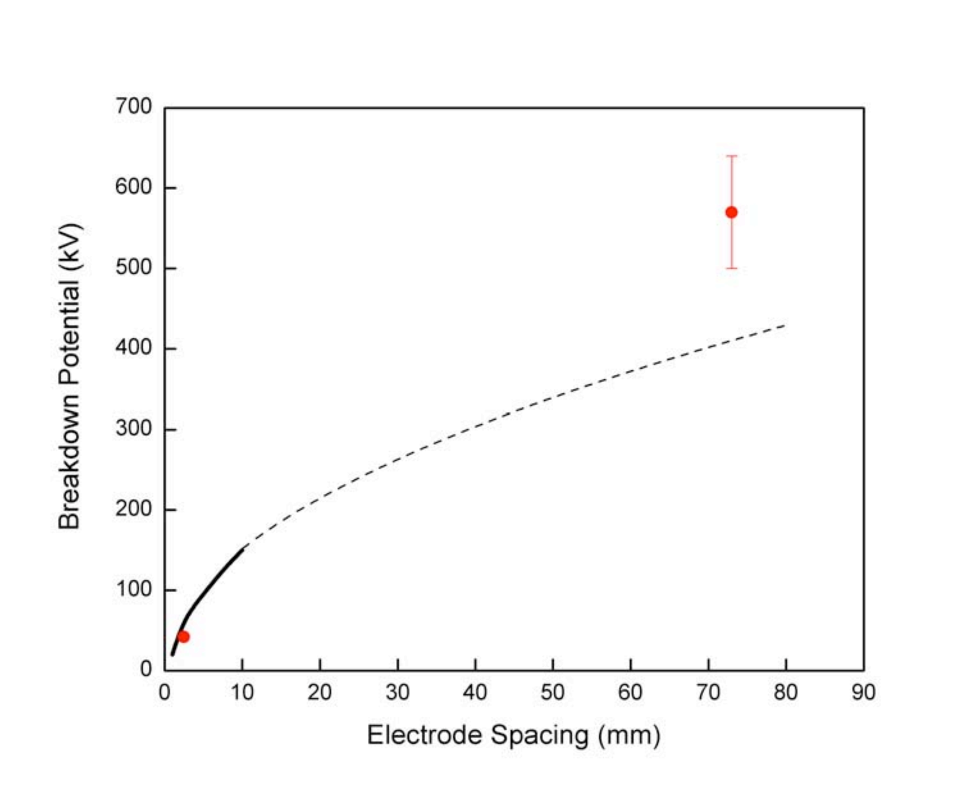
full scale test apparatus





High Voltage System

- Normal State LHe holds 570 kV at 7.3 cm (≈ 40% higher than "expected")
- Design field (50 kV/cm) at 7.3 cm holds for > 11 hr
- Max leakage current:20 pA (3% of tolerable limit)
- Short-duration breakdown not affected by neutron radiation ($10^6 s^{-1}$, MeV)



Exceeds specifications

Progress in Other Areas

- The diffusion of helium-3 in superfluid helium-4 has been measured and characterized; this is an important parameter for controlling the geometric phase systematic
- Ultracold Neutrons were produced at LANSCE by scattering cold neutrons in superfluid helium; 180 second cell lifetime was due to the superfluid fill hole. Production rate extrapolated to improved moderator, higher target current, better guides is 0.5/cc/sec, implying 250/cc UCN density at FP12 of LANSCE
- A helium isotopic purification apparatus has been operated
- A baseline model along with realistic technical scheme for operating the experiment has been developed
- We have acquired and operated a dilution refrigerator

EDM Experiment at the SNS