neutron EDM with SuperFluid ^{4}He (and ^{3}He) Experiment

Kent Leung (on behalf of the nEDMSF collaboration)

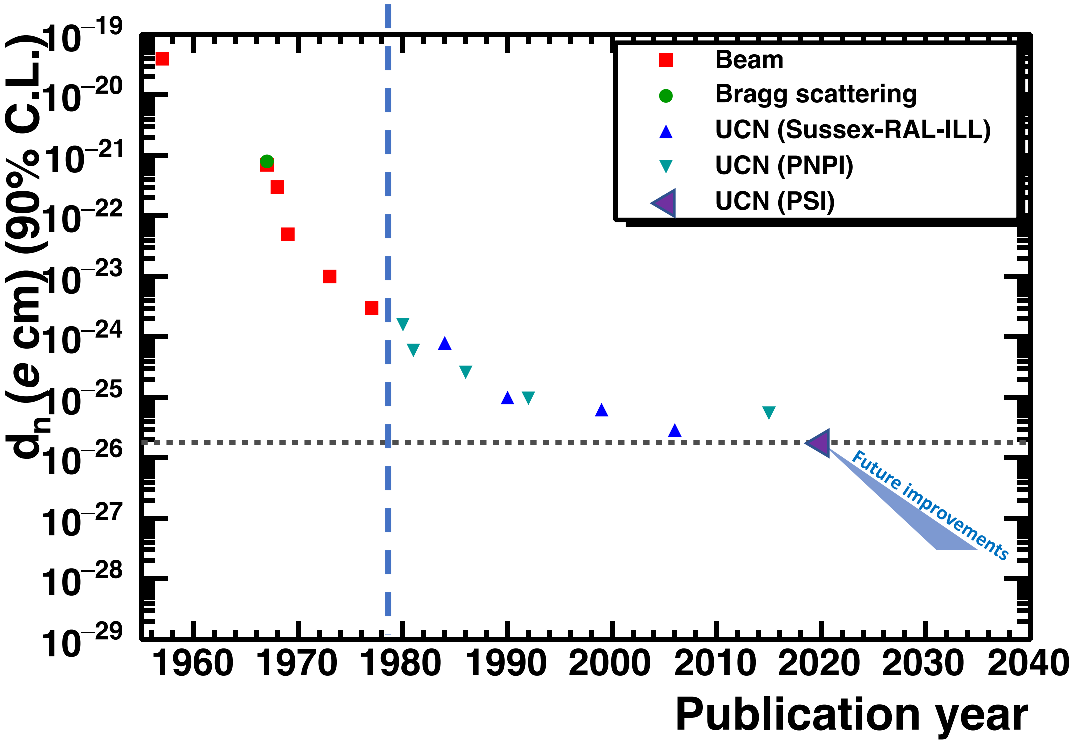
"Electric Dipole Moments: Experimental and Theoretical Horizons"

Caltech, May 12-14, 2025

Organized by Caltech and the T.D. Lee Institute, Shanghai

MONTCLAIR STATE UNIVERSITY

Neutron EDM sensitivity



From: "Electric dipole moments and the search for new physics" (2022 community white paper) arxiv:2203.08103

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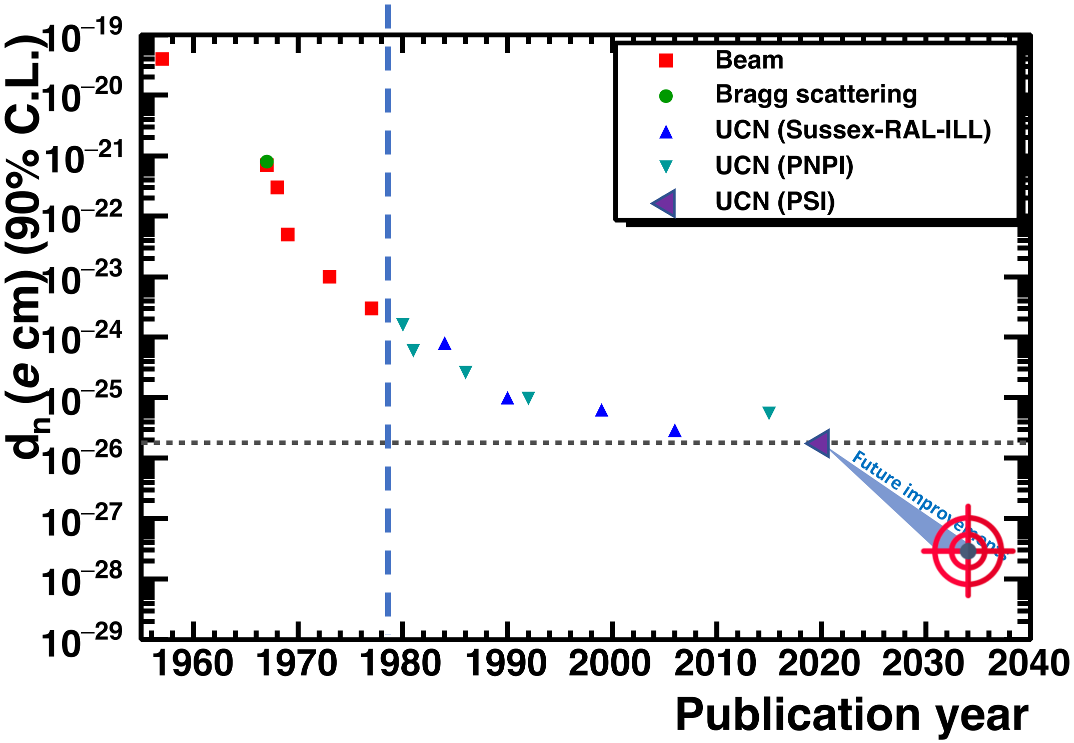

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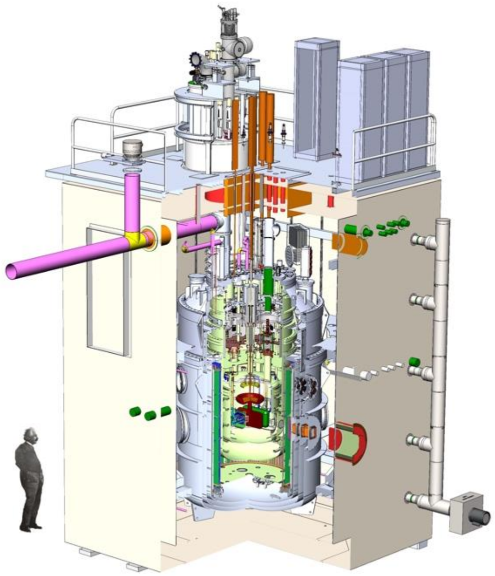
nEDMSF's new approach



- Funding for the "legacy" nEDM@SNS was cancelled by US Department of Energy (Office of Science) in Nov. 2023
  - History: collaboration was formed in ~ 2002
  - First funding from DOE/NSF in ~2012-14
  - Total was ~ $58M by DOE count
  - About half the apparatus has been constructed
  - Cancellation letter noted that the experiment had overcome *"a number of impressive technical challenges … and in some cases developing new technical solutions that have value on their own"* but also that there remained a *"low state of technical readiness for critical subsystems"*
  - Had a significant R&D component remaining

Institut Laue-Langvin (France)

- Based on the investment to date, we start building up the measurement technique in a **staged approach**
  - **New international nEDMSF collaboration formed**
  - Neutron sources: **Institut Laue-Langevin (France) & European Spallation Source (Sweden)**
  - Incorporate what we learn AND new ideas into subsequent steps

European Spallation Source (Sweden)

Jan 2024 & Nov 2024 letters from Europe to:

Dr. Paul Mantica
Facilities and Project Management Division
Office of Nuclear Physics (NP)
U.S. Department of Energy
19901 Germantown Rd.
Germantown, MD 20874

Dr. Allena Opper
Program Director, Nuclear Physics - Experiment
National Science Foundation
2415 Eisenhower Avenue
Alexandria, VA 22314

Dr. Timothy Hallman
Associate Director of Science for Nuclear Physics
US Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585-1290

We […] suggest an **evolution of the project's achievements towards a larger international collaboration** for a cryogenic neutron EDM measurement **hosted at the best possible neutron source in the world.**

[…] the **U.S. contribution to the new collaboration** would therefore be, in first order, the **in-kind transfer of equipment as well as operational support for the U.S. groups to participate**. […] the **US would remain the major player within the collaboration** with corresponding weight in key decisions regarding project evolution.

We […] give our **strongest support for the future nEDMSF project** […]. Beam time proposals of this collaboration were recently **evaluated by ILL's scientific subcommittee and the scientific excellence was clearly recognized**. The subcommittee highlighted the **strategical importance of this future-of-the-field-defining experiment** and **recommended ILL to support this program**. The critical importance of such a global nEDM program is also **endorsed by nuclear and particle physics communities** within the **NUPECC Long range plan and the European Strategy for Particle Physics.**

ILL's management and subcommittee **welcome the proposed staged approach** […].

Dr. Ken Andersen
Director
Institut Laue-Langevin
Tel: +33 (0)4 76 20 7100
e-mail: andersen@ill.eu

Yours sincerely,

Ken Andersen ILL Director	Jacques Jestin ILL Science Director	Helmut Schober ESS Director	Giovanna Fragneto ESS Science Director
[signature]	[signature]	[signature]	[signature]

Staged Approach to Experiment Realization I

- A proof-of-principle for 3 key techniques in the experiment

Phase 1 (Institut Laue-Langevin's PF1B cold neutron beam)

- Ultracold Neutron production in superfluid & detection of n + ^{3}He capture light in a (legacy) measurement cell (largely existing apparatus)

Phase 2 (Institut Laue-Langevin's PF1B cold neutron beam)

- UCN production, detection of capture light & *polarization* (largely existing apparatus)

Phase 3

- Superfluid HV test with Cavallo multiplier, realistic electrodes, measurement cell (significant existing apparatus)

International Collaboration for Phase I experiments at the Institut Laue-Langevin

1	Brad Filippone	*Caltech*	**16**	Weijun Yao	*Oak Ridge National Laboratory*
2	Skyler Degenkolb	*Heidelberg University*	**17**	Maurits van der Grinten	*Rutherford Appleton Laboratory*
3	Hanno Filter	*Institut Laue Langevin*	**18**	David Milstead	*Stockholm University*
4	Tobias Jenke	*Institut Laue Langevin*	**19**	Peter Fierlinger	*Technical University of Munich*
5	Michael Jentschel	*Institut Laue Langevin*	**20**	Robert Georgi	*Technical University of Munich/FRM II*
6	Oliver Zimmer	*Institut Laue Langevin*	**21**	Thomas Neulinger	*Technical University of Munich/FRM II*
7	Benoit Clément	*Laboratoire de Physique Subatomique & Cosmologie*	**22**	Florian Piegsa	*University of Bern*
8	Kent Leung	*Montclair State University*	**23**	Doug Beck	*University of Illinois at Urbana-Champaign*
9	Robert Golub	*North Carolina State University*	**24**	Chen-Yu Liu	*University of Illinois at Urbana-Champaign*
10	Paul Huffman	*North Carolina State University*	**25**	Chris Crawford	*University of Kentucky*
11	Ekaterina Korobkina	*North Carolina State University*	**26**	Wolfgang Korsch	*University of Kentucky*
12	Vince Cianciolo	*Oak Ridge National Laboratory*	**27**	Brad Plaster	*University of Kentucky*
13	Paul Mueller	*Oak Ridge National Laboratory*	**28**	Valentina Santoro	*University of Lund*
14	John Ramsey	*Oak Ridge National Laboratory*	**29**	Clark Griffith	*University of Sussex*
15	Andy Saunders	*Oak Ridge National Laboratory*	**30**	Steve Lamoreaux	*Yale University*

Staged Approach to Experiment Realization II

- Three major areas requiring further development

High voltage

- Complete development of HV delivery, robust electrode material
  - LN2 testing of Cavallo multiplier at LANL ongoing

Composite vessels

- Vessel holding ~1400 L of superfluid helium in AC magnetic field (spin dressing)
  - Have started working with Rutherford Appleton Laboratory/Sussex to continue existing development

Helium-3 services

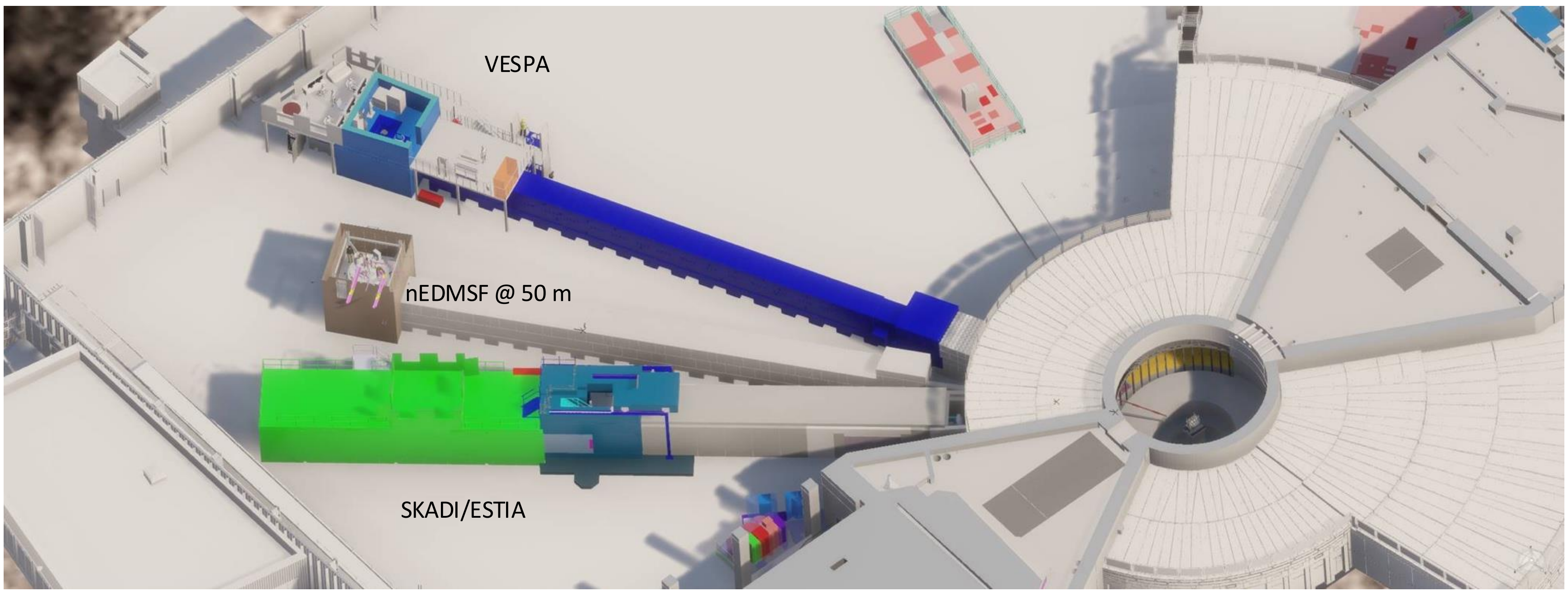
- Completion of system to add polarized ^{3}He, then remove it after measurement

Many opportunities for new contributions!

Staged Approach to Experiment Realization III

- The physical scale of a superfluid experiment is difficult to accommodate at ILL
- Have started working with ESS collaborators on possible beamline design
  - Published ANNI beamline design has ~10 x flux of at SNS*
- Engineering on beamline @ ESS started (March 2025)
- Expect higher cold neutron flux (at 1 meV) c.f. SNS

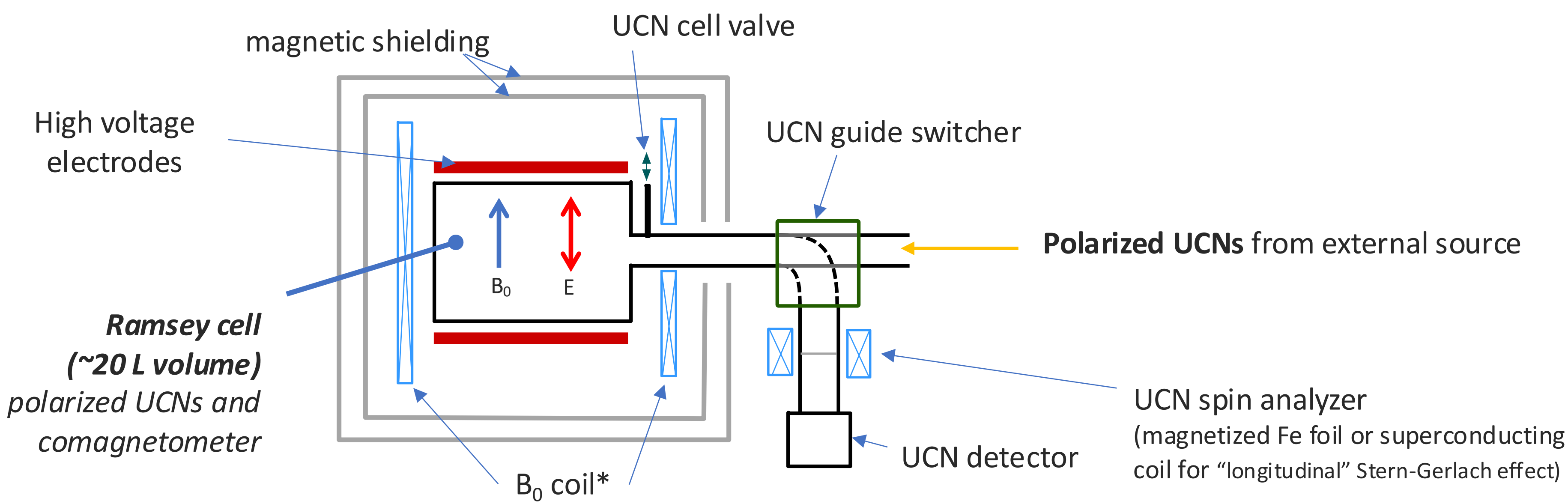
EUROPEAN SPALLATION SOURCE



* new, “existing” guide in monolith will reduce the flux by factor ≤ 2

Experimental Overview

"Traditional" Ramsey nEDM experiment with UCNs



At the **end of free precession** (i.e. at a single time), neutrons' **final phase** measured by counting number of spin down N_{down}.

(which is done **ex-situ** for UCNs measurements)

(modern experiments also measure N_{up} for normalization & have two cells with opposite E-field)

“Always measure frequency…” (Rabi? Ramsey? Wieman?)

- Control and measurements of time/clocks can be done to a high precision.
  - ✓ used in Ramsey technique

- **BUT** the power of a frequency measurement is needing only the ***relative* change** of a signal **over short time scales**
  - Drifts in system on time scales greater than a few oscillations are suppressed

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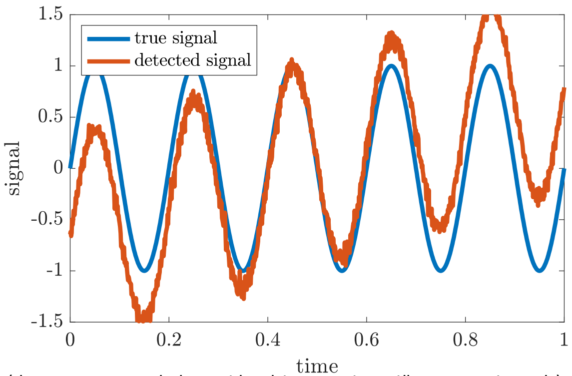

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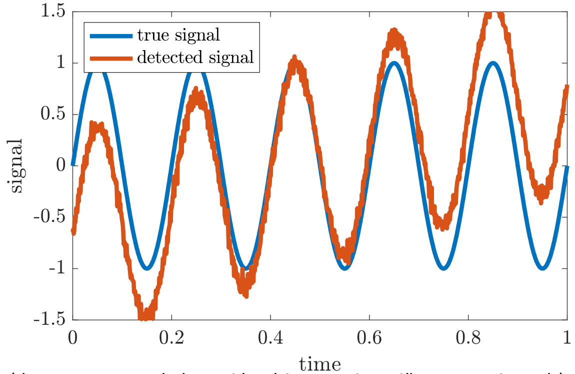
- Recall: **Ramsey’s technique** only measures **final neutron phase via. counting neutrons**. (Can’t know the frequency at all times.)
- **Need two** (possibly four) **separate repeated Ramsey cycles** (with different clock frequencies within the same cell) to **determine a single EDM value.**
- Each cycle takes ~100-200s. **A lot can happen in this time**:
- Detector efficiency drifts, magnetic field drifts, $\pi/2$ efficiency and other polarization drifts, UCN source intensity drifts, etc..
- Can be corrected but introduces additional statistics & systematics which becomes more difficult **for 10^{-28} e.cm level**



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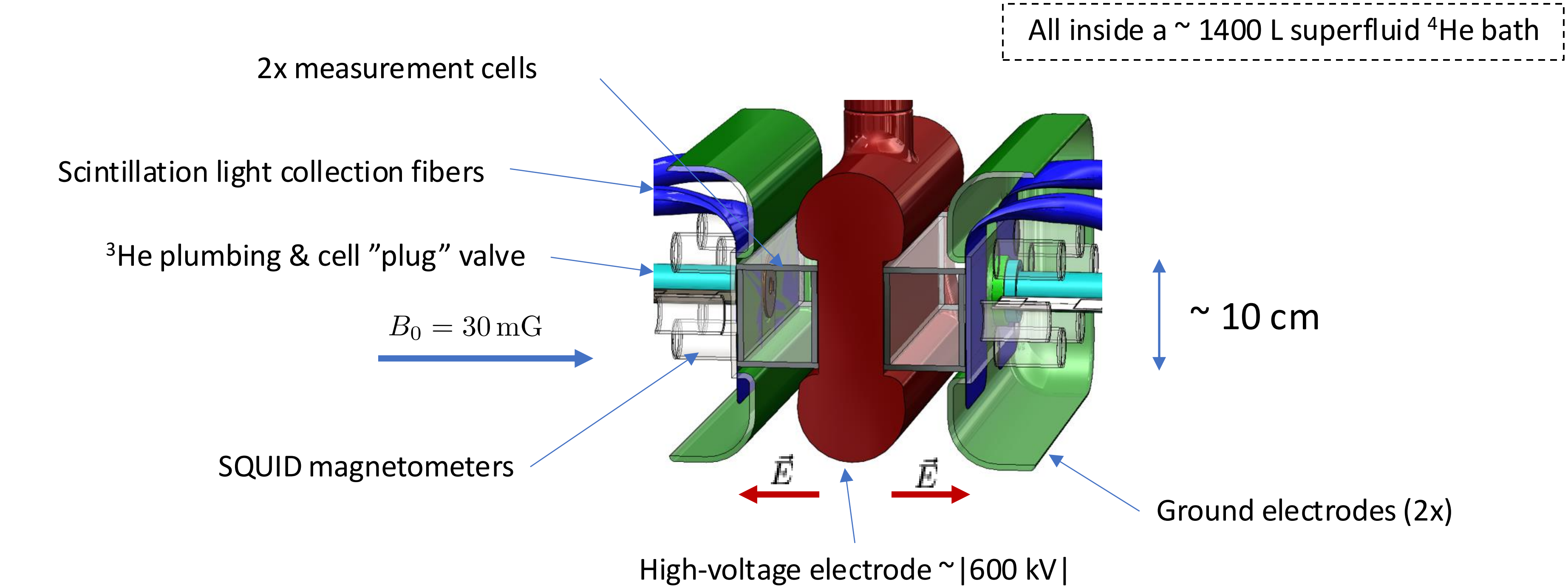
nEDMSF: UCNs + superfluid ^{4}He + polarized ^{3}He

Based on Golub & Lamoreaux, Phys. Rep. (1994)



- **Double cell** setup with E-field relative to B-field opposite in each cell
- **>95% polarized ^{3}He** loaded into cell (dissolved in isotopically-pure superfluid ^{4}He at 0.4 K).
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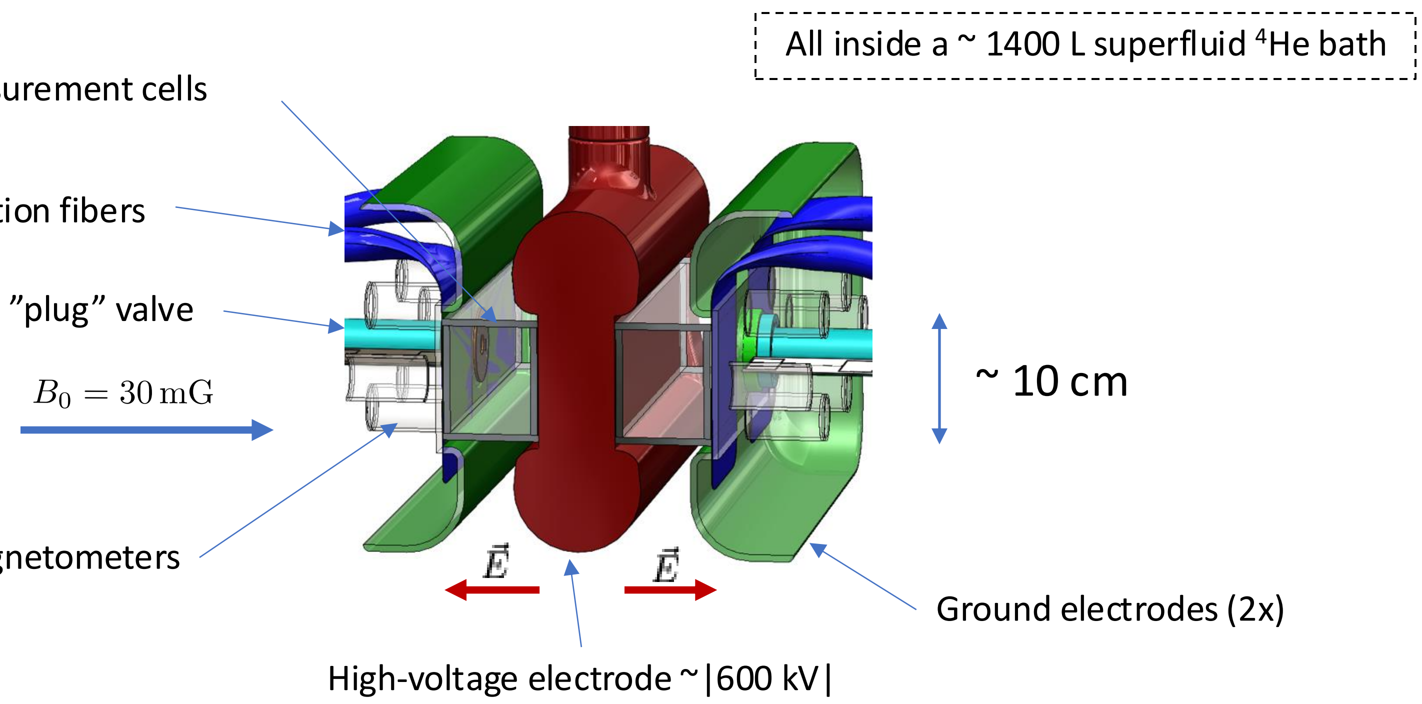

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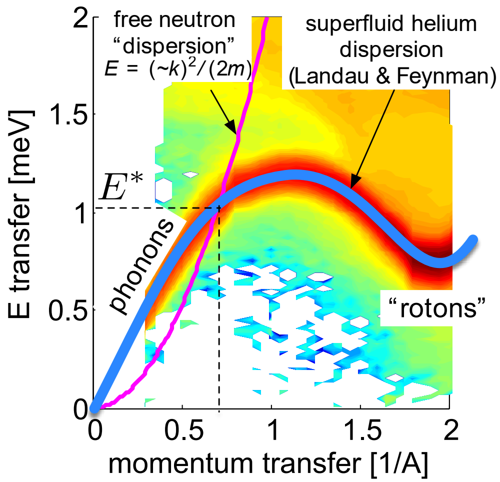
- **In-situ super-thermal UCN (~ 100 neV) production** and accumulation in **superfluid ^{4}He with polarized 1 meV cold neutron beam** (direction into the page).
- Cold neutron beam ~ 100% polarized -> produce ~ 100% UCNs polarized.

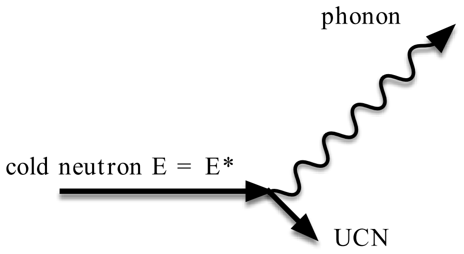
Roles of the superfluid ^{4}He

- **1 meV cold neutrons (11 K) scatter off phonons** in superfluid ^{4}He to become **UCNs (< 160 neV, "2 mK")**

Log contour plot of dynamic structure factor of He-II @ 1.2K from [Andersen et al. J. Phys. Condens. Matter (1994)]



Down-scattering from single phonon (~ T independent):



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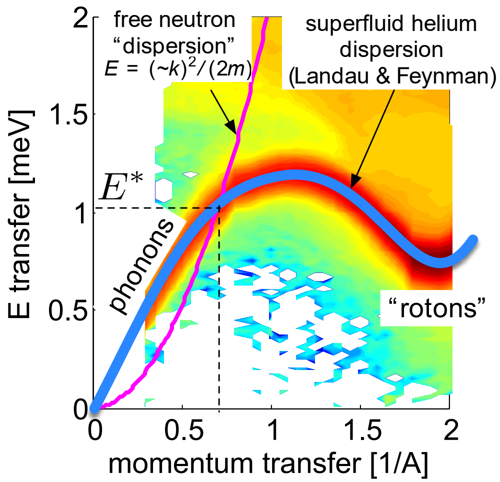

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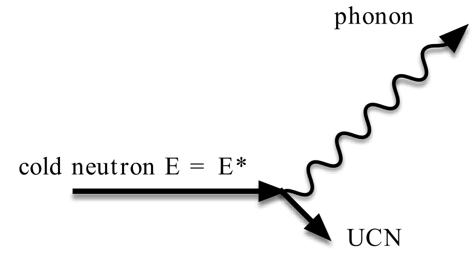
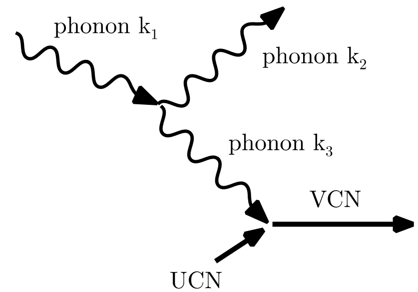


Dominant UCN loss is two-phonon scattering:

$$\tau_{\mathrm{up,2-phonon}} = (100\,\mathrm{s\,K^7})\,T^{-7}$$

[Golub & Pendlebury, Physics Letters A (1977)]



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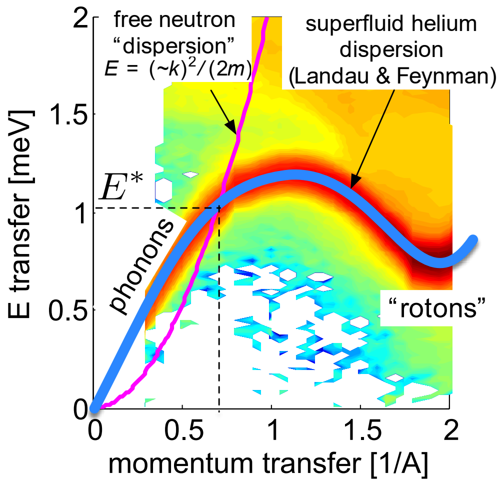

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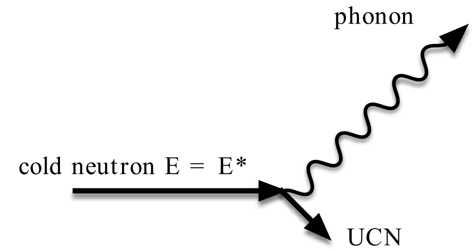

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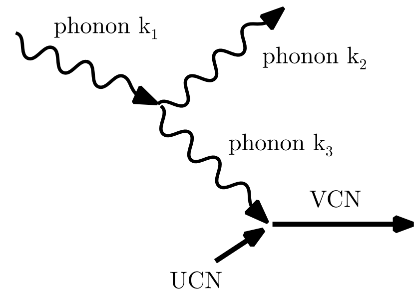

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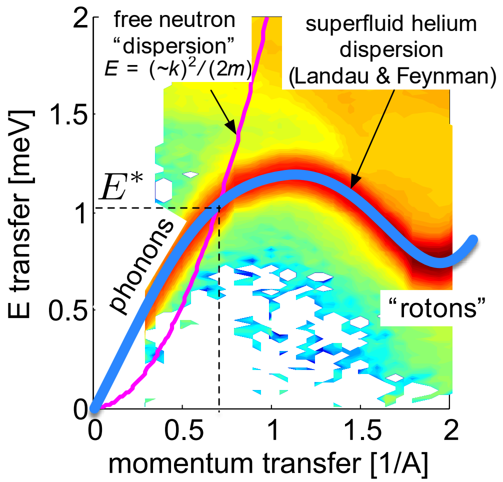

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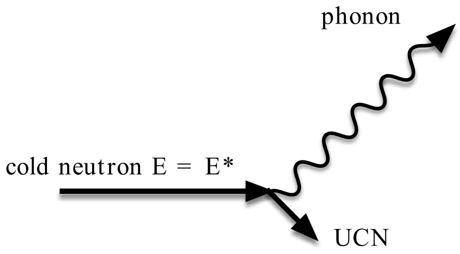

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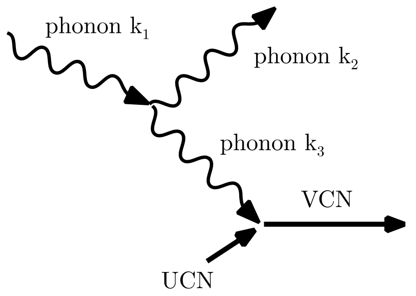

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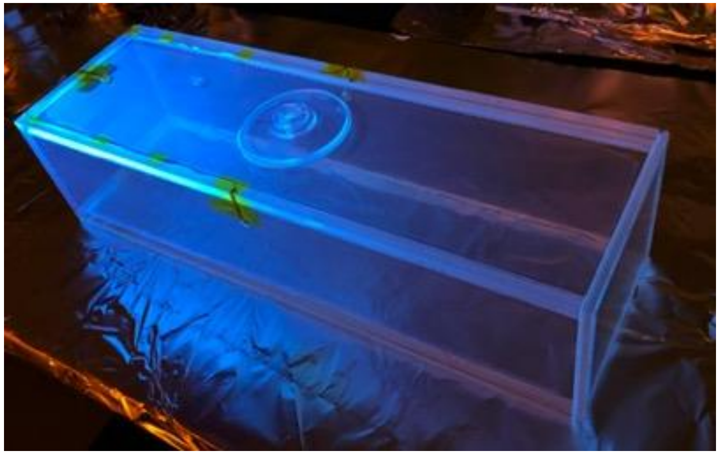
- Superfluid also **scintillates at ~ 80 nm** (EUV) ➞ used to detect n-^{3}He capture events (later)

- ^{3}He atoms scatter off phonons ➞ mean-free-path ~ $T^{7.5}$ ➞ important for key "false EDM" systematic control

Measurement cells



Full-sized prototype measurement cell illuminated by 300 nm UV lamp

- Inside: 7.5 cm (W), 10 cm (H), 40 cm (D) rel. to beam.
- Inner walls: **deuterated PS + d-TPB** (for fluorescent properties to detect 80 nm ^4He scintillation).
- Neutron optical potential = **170 neV**
- Design goal wall loss $\boldsymbol{\tau_{cell}}$ **= 2,000 s**

- **Cryogenic UCN storage cell** => **low wall loss**. Design goal wall loss τ_{cell} = 2,000 s. Due to unavoidable β-decay:

$$\tau_{\beta+cell} = \left(\tau_{\beta}^{-1} + \tau_{cell}^{-1}\right)^{-1} = 610\,\mathrm{s}$$

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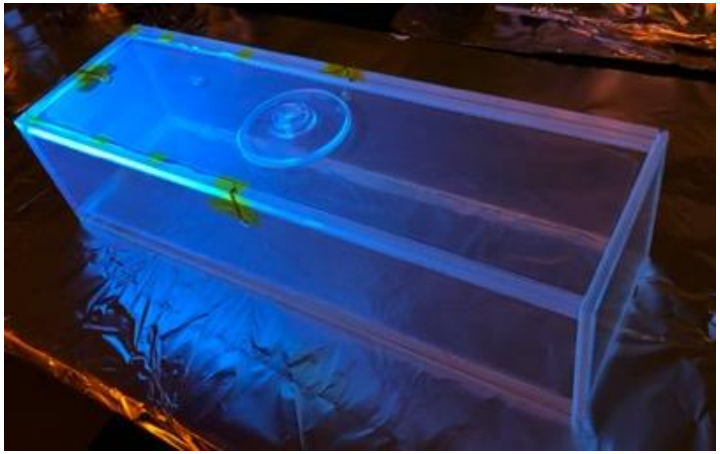

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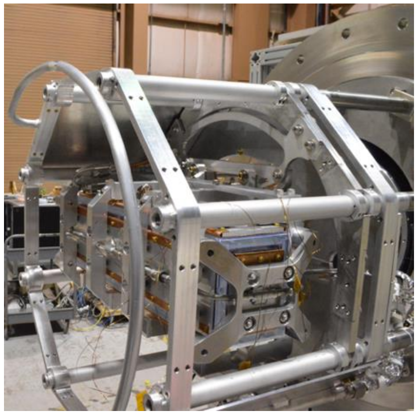
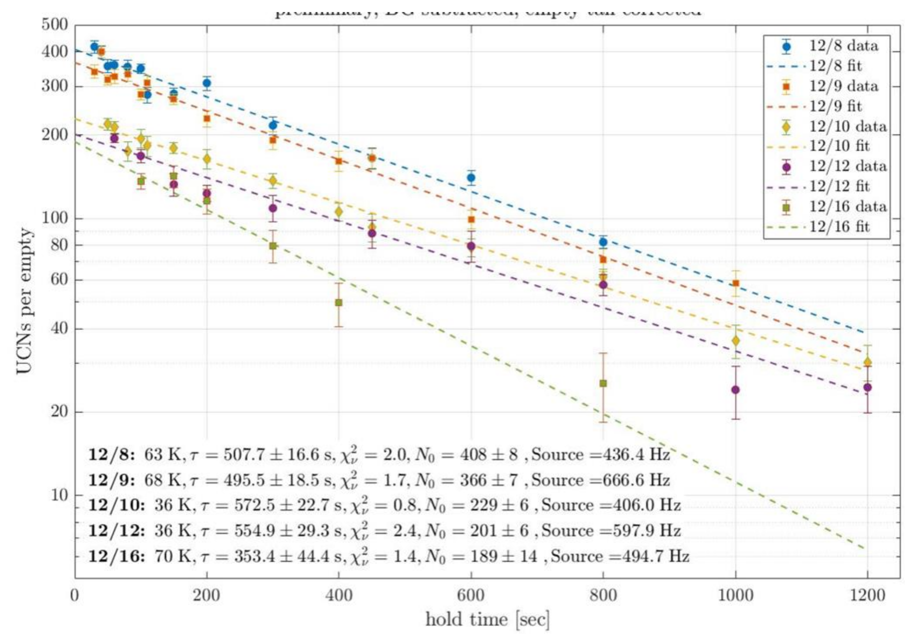
- Long $\tau_{\beta+cell}$ allows a large number of UCNs accumulated per fill. **Polarized UCN density ~180 UCN/cm^3** => ~ 500,000 UCNs per cell.

- **UCN "usefulness" time restricted by** $\boldsymbol{\tau_{\beta+cell}}$ (transverse spin coherence times are ~ 20,000 s)
- "Useful" UCN time of **1,000 s** use in a measurement cycle

Measurement cell II

Fill and empty UCN storage measurements at LANL (external UCN source)





- **Latest cell** tested at LANL UCN source had $\tau_{\beta+\text{cell}}$ of 570 ± 20 s. (Single exponential decay only observed)

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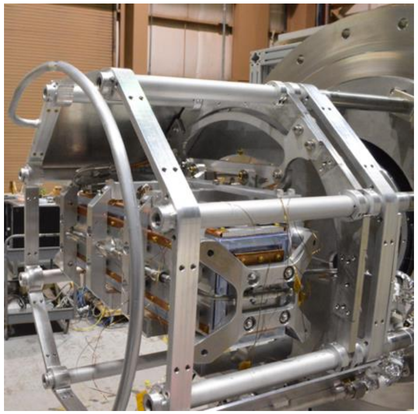

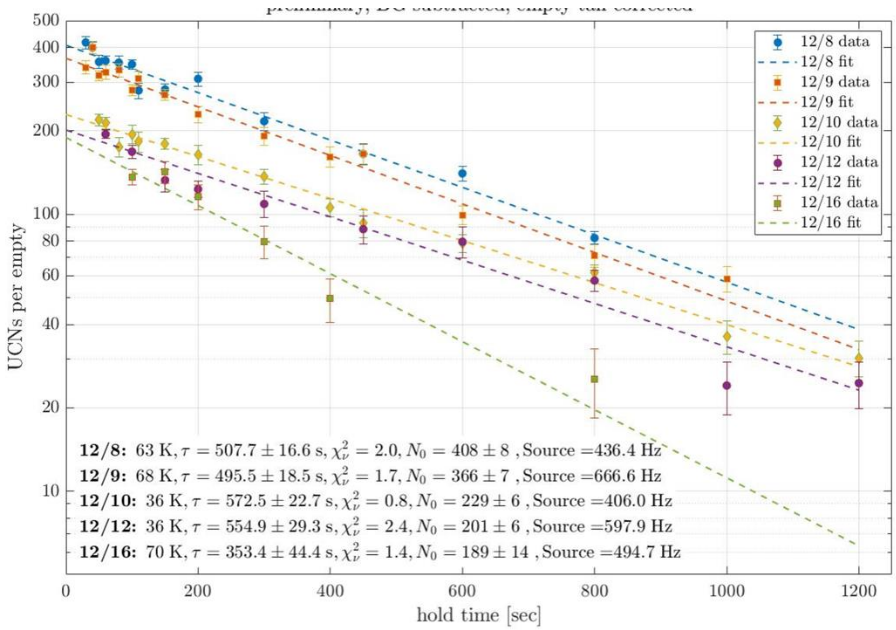

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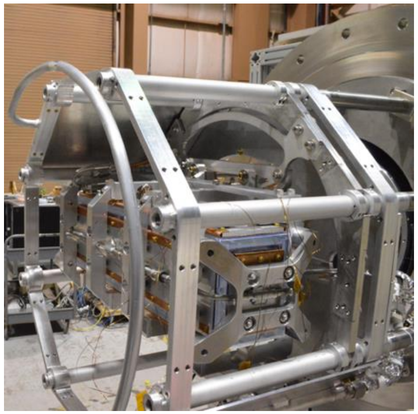

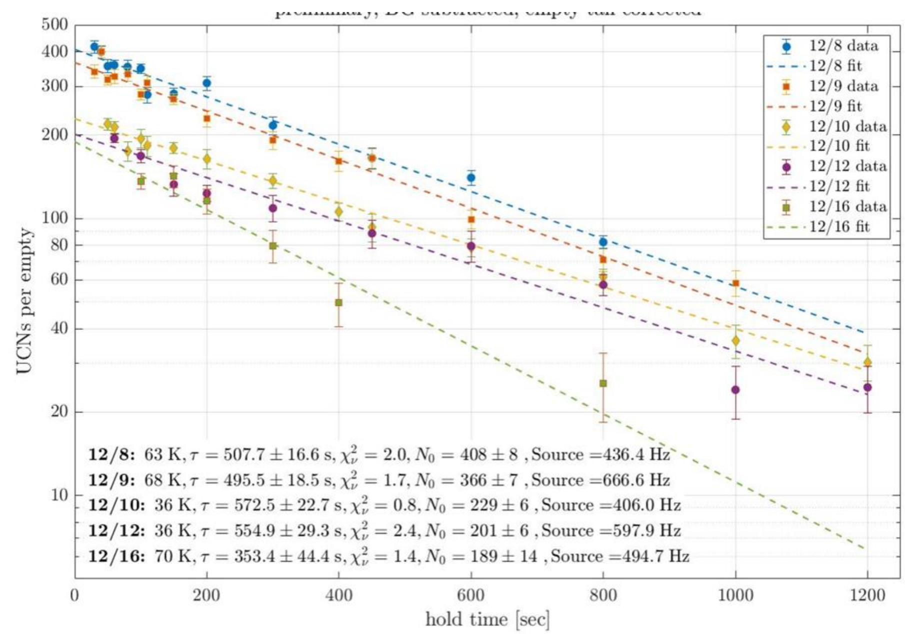

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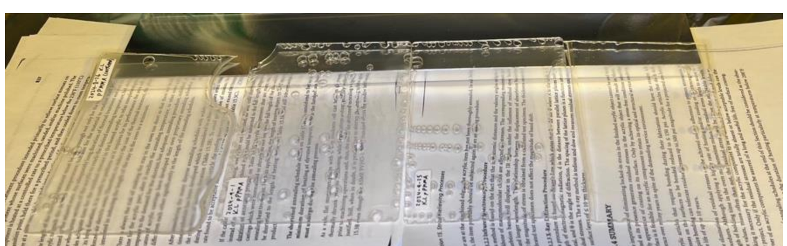
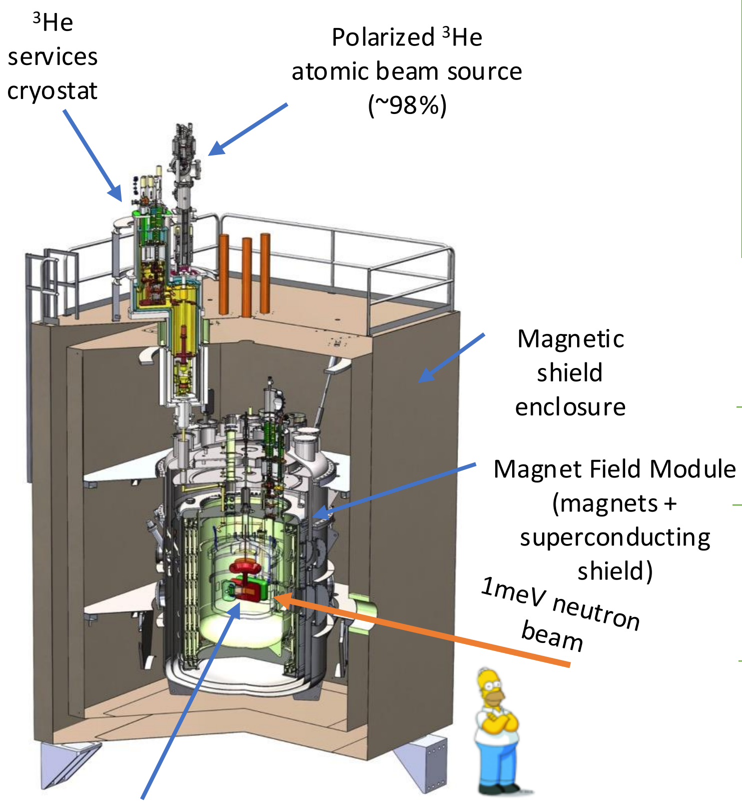
- UCN spectrum from external source different to superfluid -> building spectrometer to understand
- Disadvantage to in-situ: **cold neutron beam induced activation of cell**
  - End windows d-PMMA purity to ppm level. Recently achievement **in-house polymerized** end windows 150 Hz -> **27 Hz background (10% impact in sensitivity)**



Approximate sensitivity scaling



Statistical "shot noise" figure of merit: $\sigma(d_n) \sim \dfrac{\hbar}{2\alpha E T \sqrt{N}}$

$E =$ electric field	75 kV/cm in superfluid ^{4}He @ ~ 2 atm pressure vs ~ 10 kV/cm in vacuum
$\alpha =$ polarization contrast	(UCN & ^{3}He polarization ~ 98%)
$T =$ precession time	(we can use 1000 s vs. ~ 200 s for room temp. experiments)
$N =$ no. detected neutrons	2-3x improvement on running/close-to-running 10^{-27} e.cm experiments. We have high-density in small cells which reduces systematics (see later)

Systematics: small cell -> smaller region to achieve average field spec < 100 nG/cm.
Superconducting Pb shield -> great for suppressing field drifts

Comagnetometery

- A magnetometer species (typically a gas) that “cohabits” the same volume as the UCNs experience.
- Need sufficient comagnetometer atoms for precision; too high can cause electric breakdowns & UCN loss (~ 10^{-6} mbar)

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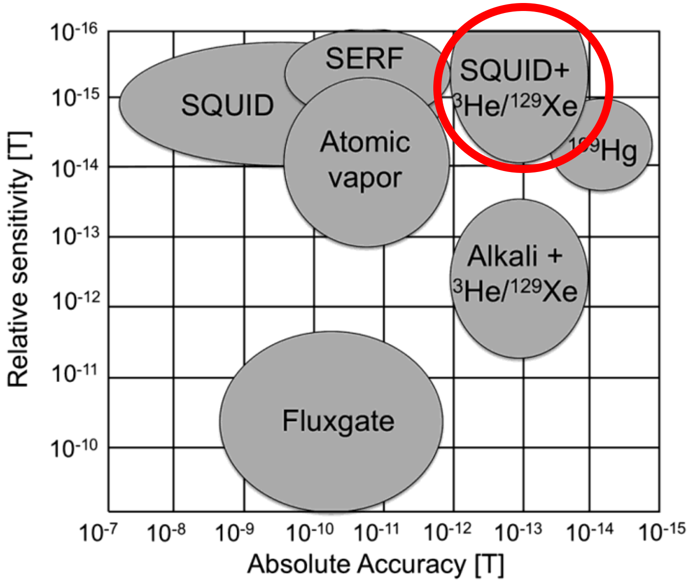

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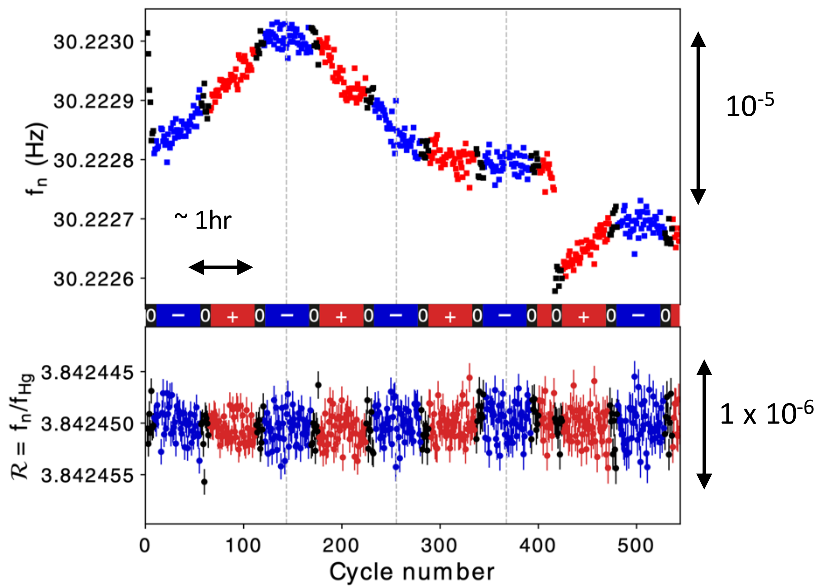

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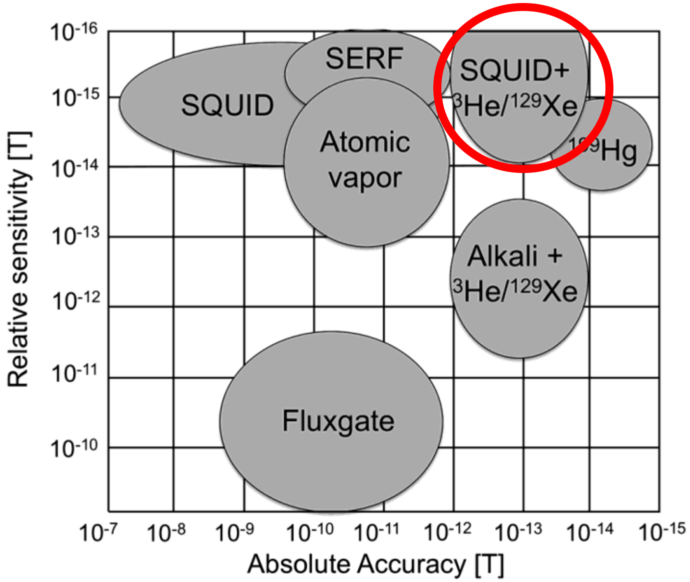

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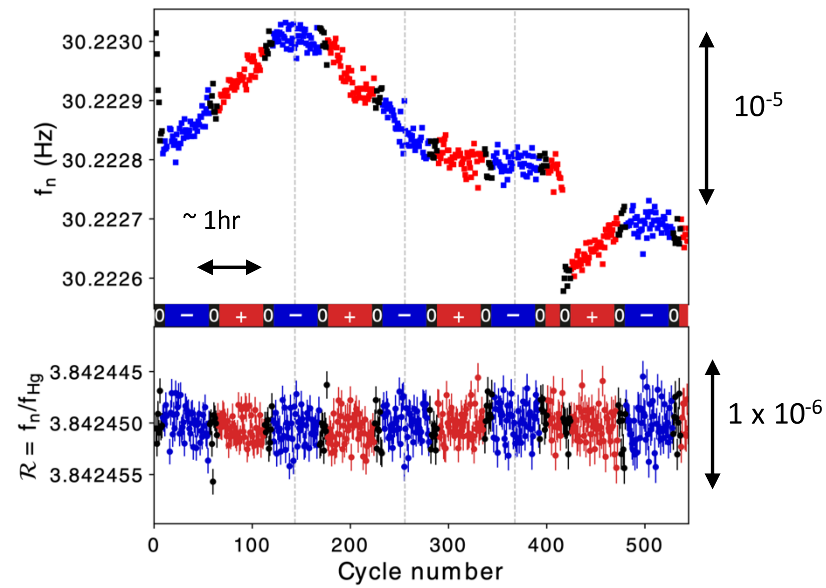

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- nEDM experiments ultimately measure relative to comagnetometer's EDM (usually "Schiff suppressed")
- However, the two species still experiences **different (time & space) averaged magnetic fields** because:
  - UCNs have such low speeds, they "sag" in gravity a few mm.
  - Relativistic $\vec{E} \times \vec{v}$ motional-field related effects are different. One produces a *false* EDM (most serious systematic error)

Polarized ^{3}He as *live and in-situ* UCN spin analyzer

- Polarized ^{3}He gas cells widely used as neutron beam spin analyzers (count survivors)
- Strong **spin-dependent capture cross-section**: $^3\overrightarrow{\mathrm{He}} + \overrightarrow{\mathrm{n}} \rightarrow \mathrm{p} + {}^3\mathrm{H} + 764\,\mathrm{keV}$

Anti-parallel spins: $\sigma_{\downarrow\uparrow,\mathrm{thermal}} \approx 11\,\mathrm{kb}$

Parallel spins: $\sigma_{\uparrow\uparrow,\mathrm{thermal}} \lesssim 0.1\,\mathrm{kb}$

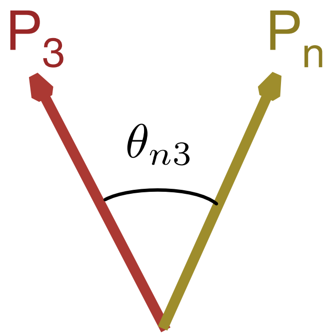
- **Capture rate** for polarized UCNs and ^{3}He in same volume :

$$\dot{N}_3 = N_{\mathrm{UCN}}\,\bar{\tau}_3^{-1}\,(1 - P_n P_3 \cos\theta_{n3})$$

number of UCNs (N_{UCN}) — polarizations ($P_n P_3$) — **angle between spins** (θ_{n3})

where $\bar{\tau}_3^{-1} \approx [n_3\,\sigma_{\downarrow\uparrow,\mathrm{thermal}} \times (2200\,\mathrm{m/s})]/2$

^{3}He number density (n_3)



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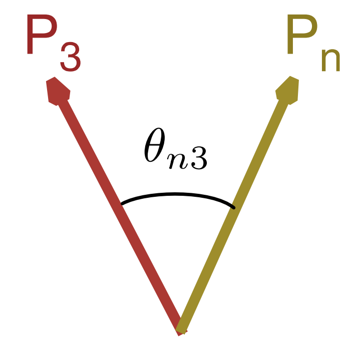

- Detect the 760 keV scintillation as generated ➞ **in-situ and live** (or "continuous") UCN spin analyzer
  - 80 nm scintillation light -> blue photons (walls of cells) -> wavelength shifting fibers -> optical fibers -> Silicon Photomultipliers

Live & in-situ UCN spin analysis

- Can’t look **too intensely** or will kill UCNs too quickly

- Want ^{3}He-n capture rate to be similar to UCN loss time (cell + β), i.e. $\bar{\tau}_3 \approx 500\,\mathrm{s}$

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- This n_3 & P_3 of ^{3}He produces ~ 6 fT fields → **detectable by SQUIDs.**

^{3}He can be used as comagnetometer AND live & in-situ UCN spin analyzer!

False EDM systematic effect

- Recall: nEDM is measured relative to the comagnetometer's EDM. Most effects cancel out with opposite E-field.
- Comagnetometer's EDM suppressed by Schiff screening but **can experience a false EDM**
- From *interaction* between the $\vec{E} \times \vec{v}$ motional field and magnetic field gradients ("geometric-phase induced false EDM")

Radius of cell

- "Discovered" in the nEDM field, false EDM for comagnetometer: $d_{af} = \frac{J\hbar}{4}\left(\frac{\partial B_{0z}}{\partial z}\right)\frac{\gamma^2 R^2}{c^2}\left[1 - \frac{\omega_0^2}{\omega_r^{\dagger 2}}\right]^{-1}$

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(Simplified cylindrical cell but general relationships hold. Rectangular cell work by Swank & Golub Phys. Rev. A **93**, 062703 (2016))

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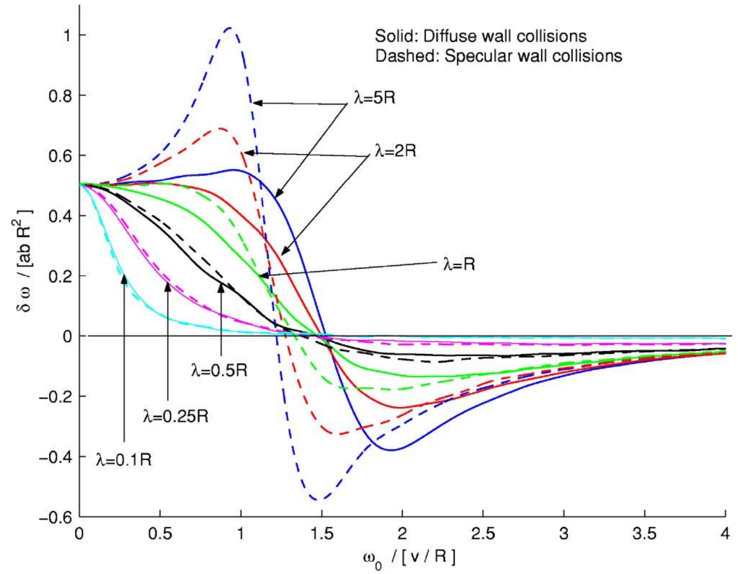
- Can change ^{3}He-phonon scattering mean-free-path by changes in superfluid temperature:

$$\lambda_{3\mathrm{He}} \approx 0.077\,\mathrm{cm} \times \left(\frac{0.45\,\mathrm{K}}{T}\right)^{15/2}$$

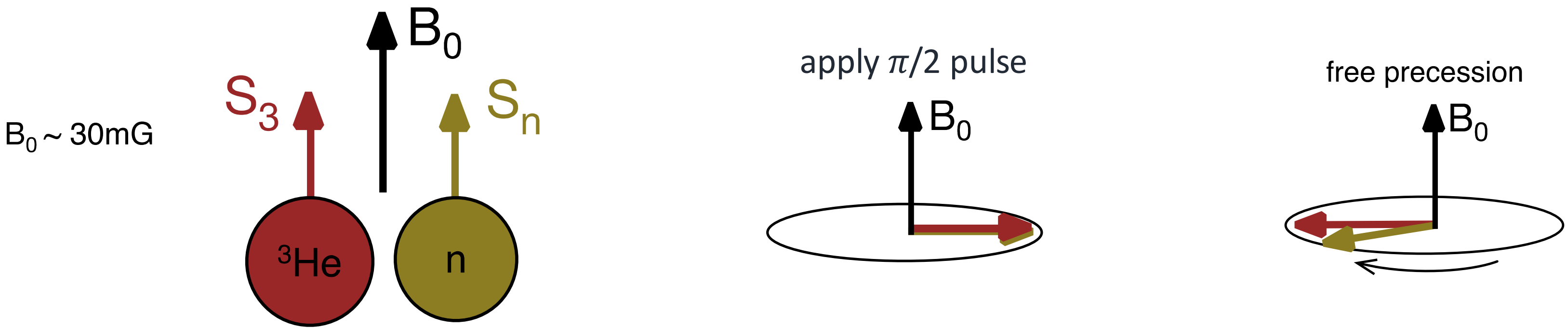
Can tune temperature to make false EDM zero by scanning T!

Numerical calculations from Golub:



Two measurement modes of nEDMSF: double free precession & critical dressed spin

Double free precession mode



- Time evolution of phase: $\theta_{3n}(t) = \theta_3(t) - \theta_n(t) = \left[(\gamma_n - \gamma_3)B_0 \pm \frac{2d_n|E|}{\hbar}\right] t + \phi_0 \equiv \omega_{3n}^{\pm} t + \phi_0$,
- With B_0 = 30 mG : $\gamma_3 B_0/(2\pi) \approx 100\,\mathrm{Hz}$ $\gamma_3 \approx 1.1\,\gamma_n$
- Scintillation light oscillation frequency: $|\gamma_n - \gamma_3| B_0/(2\pi) \approx 10\,\mathrm{Hz}$
- The transverse spin coherence time (wall depolarization + gradient depolarization), T_2 ~ 10,000 s
- Flipping high-voltage electrode often with known sequences to suppress 1^{st} order drifts (e.g. + - - + - + + -) and analysis as a ”super-asymmetry"

Free precession scintillation signal

- "accepted" rate of scintillation light events: $\dot{N}_{\mathrm{ac-s}}(t) = N_n(t)\left(\frac{\epsilon_\beta}{\tau_\beta} + \frac{\epsilon_3}{\bar{\tau}_3}\{1 - P_3(t)P_n(t)\cos[\theta_{3\mathrm{n}}(t) + \phi_{3n0}]\}\right) + R_{\mathrm{BG}}$

Acceptance probability for β-decay events (~0.33)

Acceptance probability for n-^{3}He capture (~0.93)

Background rate (could be time-dependent)

no. UCNs in cell

recall: 500 s

polarizations

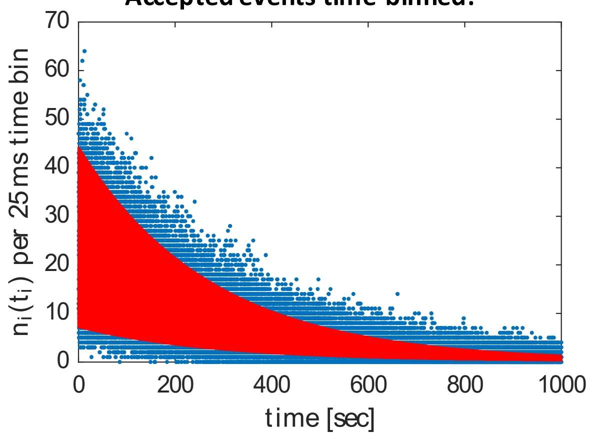
$P_3(t)P_n(t) = P_{30}P_{n0}\exp(-t/T_{2,\mathrm{tot}}) \approx (0.98)(0.98)\exp(-t/[10,000\,\mathrm{s}])$

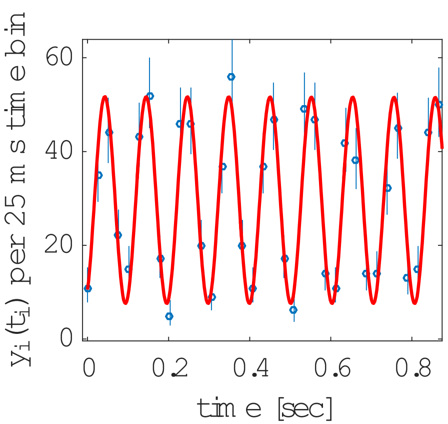
$$N_n(t) = \int_0^{E_{\max}} \mathrm{d}E\, n_{n0}(E)\exp\left[-\frac{t}{\tau_{\mathrm{cell}}(E)} - \frac{t}{\bar{\tau}_\beta} + \frac{P_n(t)P_3(t)}{\bar{\tau}_3}\int_0^t \cos\phi_{3\mathrm{n}}(t')\mathrm{d}t'\right]$$

UCN spectrum

Oscillating term due to previous n-^{3}He absorption

Accepted events time-binned:





➢ Continuously measuring the UCN phase (relative to ^{3}He) ➞ **continuous frequency measurement** (via derivative)!

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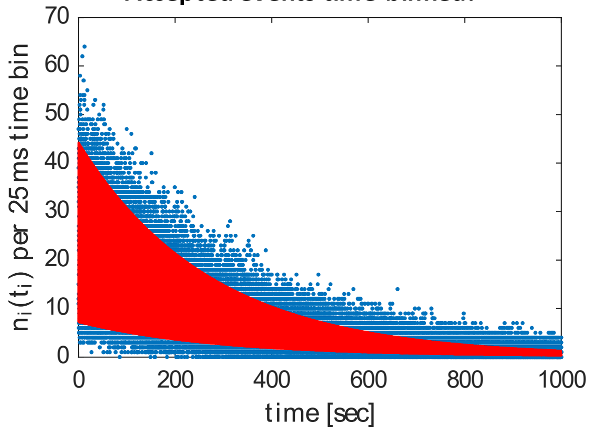
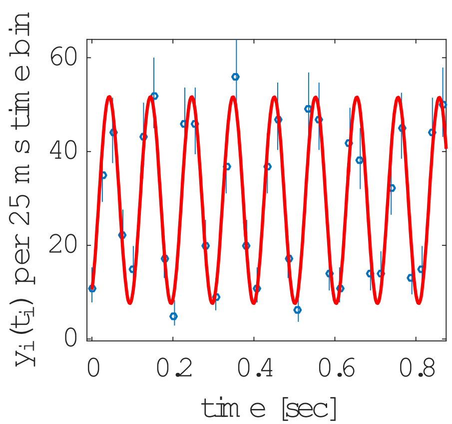
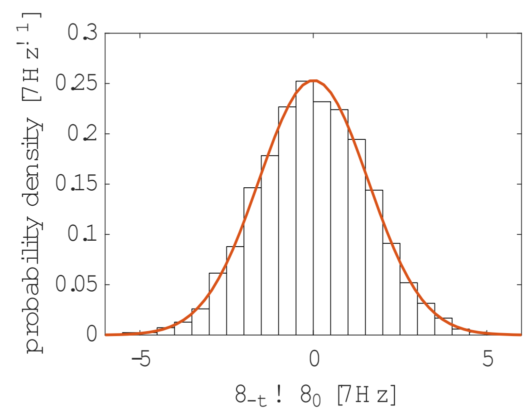




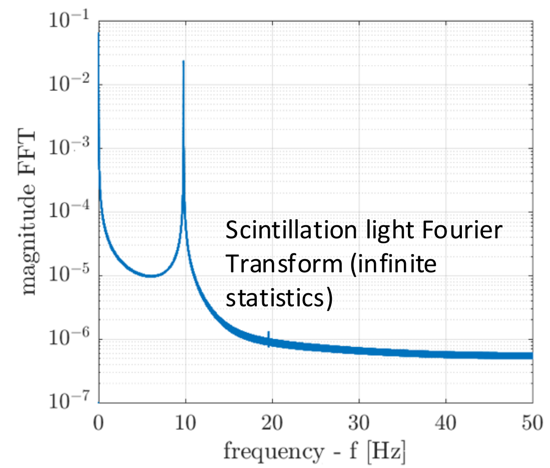
Repeat generation & fit:



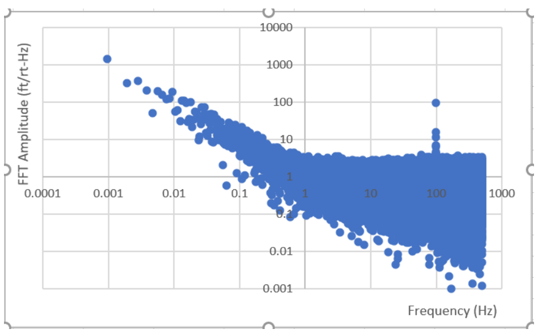
- ➢ Continuously measuring the UCN phase (relative to ^{3}He) ➞ **continuous frequency measurement** (via derivative)!
- ➢ 300 live days of running (expected to take 3 years), get **1σ nEDM error = 3 x 10^{-28} *e*.cm**

Data analysis simulations

- Neutron decay ***β*-asymmetry**
- **Spatial-variation scintillation light** detection efficiency
- **Oscillation in $N_n(t)$** due to history of n-^{3}He absorption
- **Reduced parameter "contrast" fitting** to handle UCN energy-dependent wall loss
- Generation of scintillation light data with **magnetic field drifts**
- Generation of SQUID **^{3}He signal with noise and drifts** (UKy student: Mojtaba Behzadipour)
- **Simultaneously fitting SQUID signal and scintillation light** signal with global likelihood parameter (UKy student: Mojtaba Behzadipour)
- Fit **temporal field drifts** with **orthogonal polynomials**
- **Particle-by-particle neutron** scintillation data generation code
- **Magnetic field noise** in spin-dressing mode
- **Novel** spin dressing field modulation modes (Caltech grad: Raymond Tat)
- UCN spin-tracking on **Graphics Processing Units** (NCSU/Caltech/ORNL: Morano, Tat, Matthews)
- UCN center-of-mass **gravitational offset time-evolution**

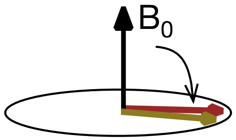


SQUID signal with noise

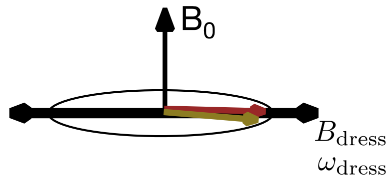


Dressed-spin mode

apply $\pi/2$ pulse



apply strong off-resonance dressing field perpendicular to B_0 to alter precession of **both species**



Cohen-Tannoudji:

$$\hat{H} = -\gamma B_0 \hat{S}_z + \hbar \omega_d \hat{a}^\dagger \hat{a} + \lambda \hat{S}_x (\hat{a} + \hat{a}^\dagger)$$

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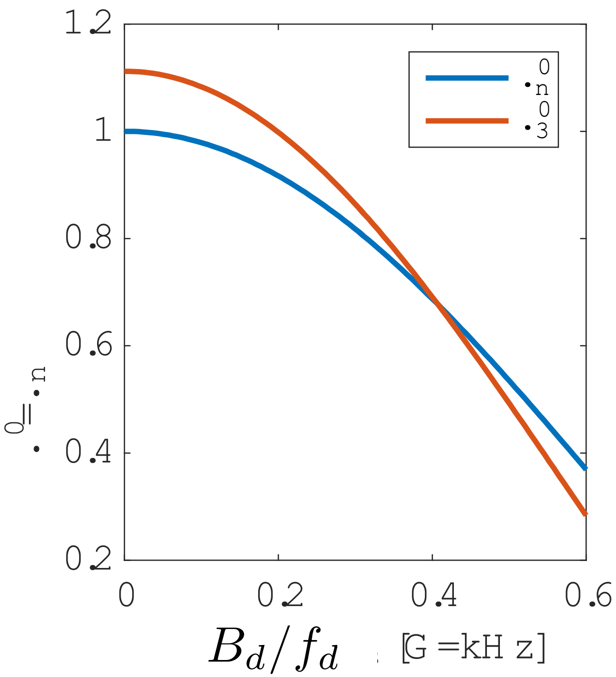
In the limit $B_{\text{dress}} \gg B_0$

effective gyromagnetic ratio

0^{th} order Bessel function

$$\gamma' = \gamma\, J_0\left(\frac{\gamma B_{\text{dress}}}{\omega_{\text{dress}}}\right)$$

original



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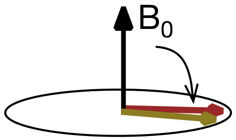

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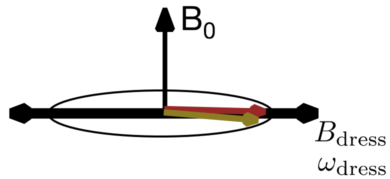

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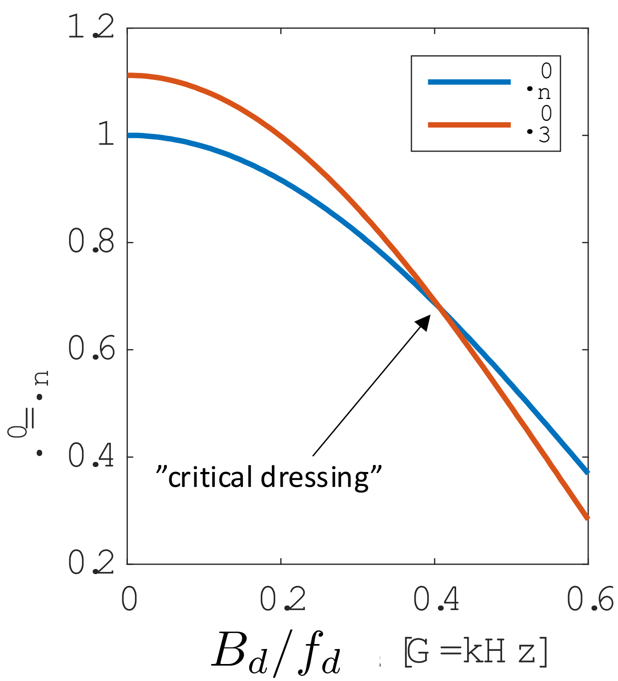

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- For instance, if $B_{\rm d} = 1\,{\rm G}$ is chosen, then $f_{\rm d} \approx 2.5\,{\rm kHz}$ is needed

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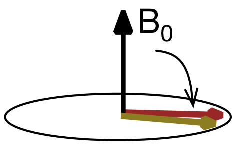

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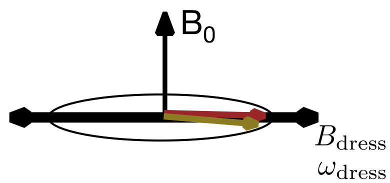

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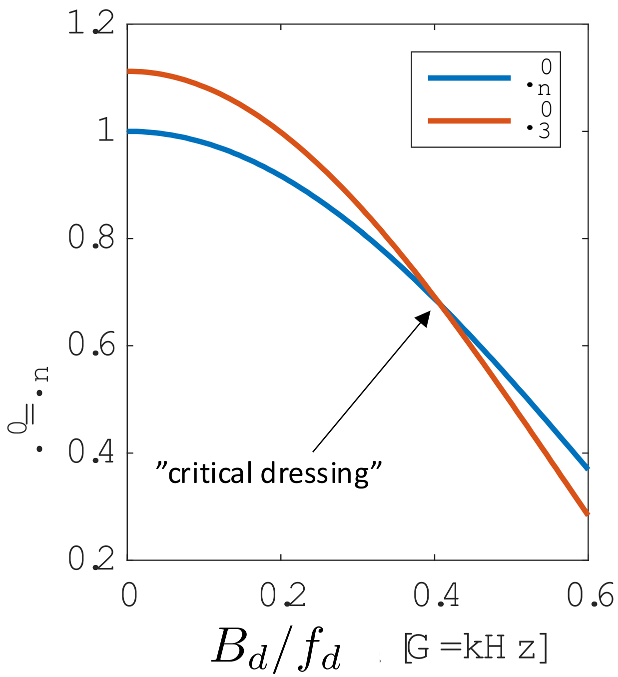

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- If above or below critical dressing condition, then **can make neutrons effectively precess faster or slower than ^{3}He** as needed.

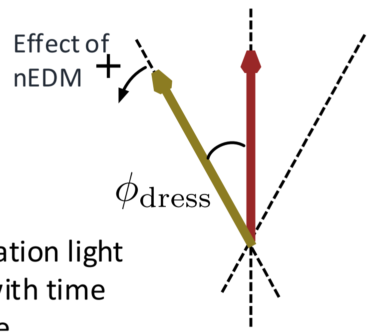
Critical modulated dressed-spin mode

- The effect of **neutron EDM** with spin dressing: $\gamma_{\rm n}' B_0 \pm \frac{2ed_n E J_0(\gamma_{\rm n} B_{\rm dress}/\omega_{\rm dress})}{\hbar}$

- Example of modulation with **"square wave pulses".** (Other modes possible.)

Critical dressing field to sit at a fixed $\phi_{\rm dress}$

(In rest frame of ^{3}He spin, B_0 coming out of screen)



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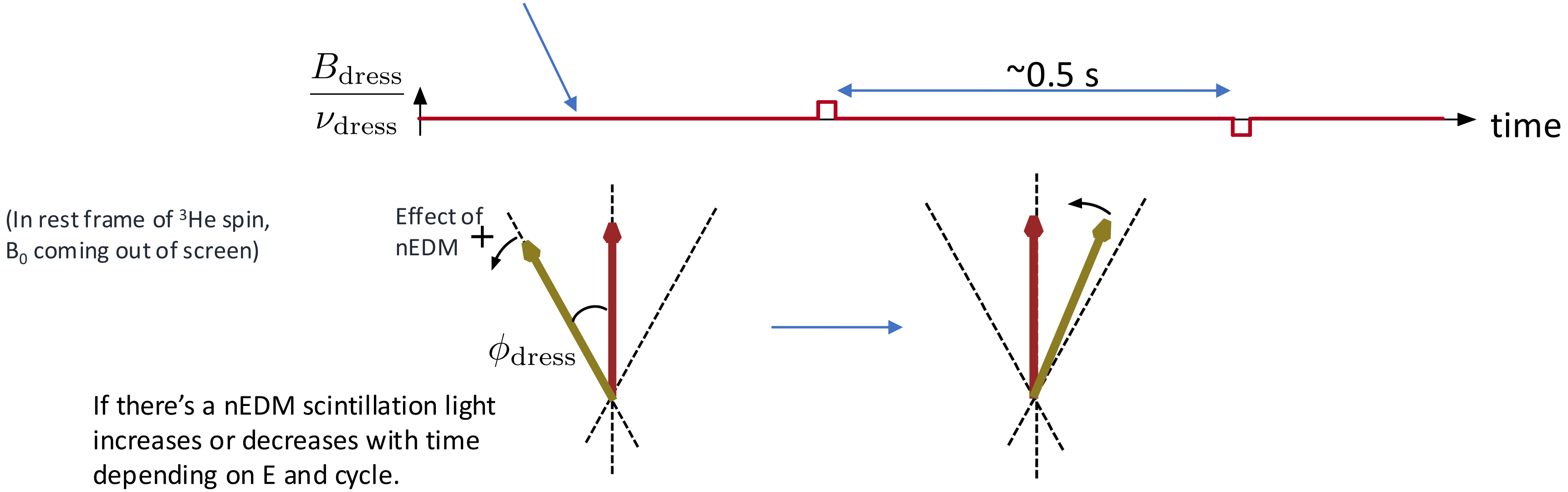

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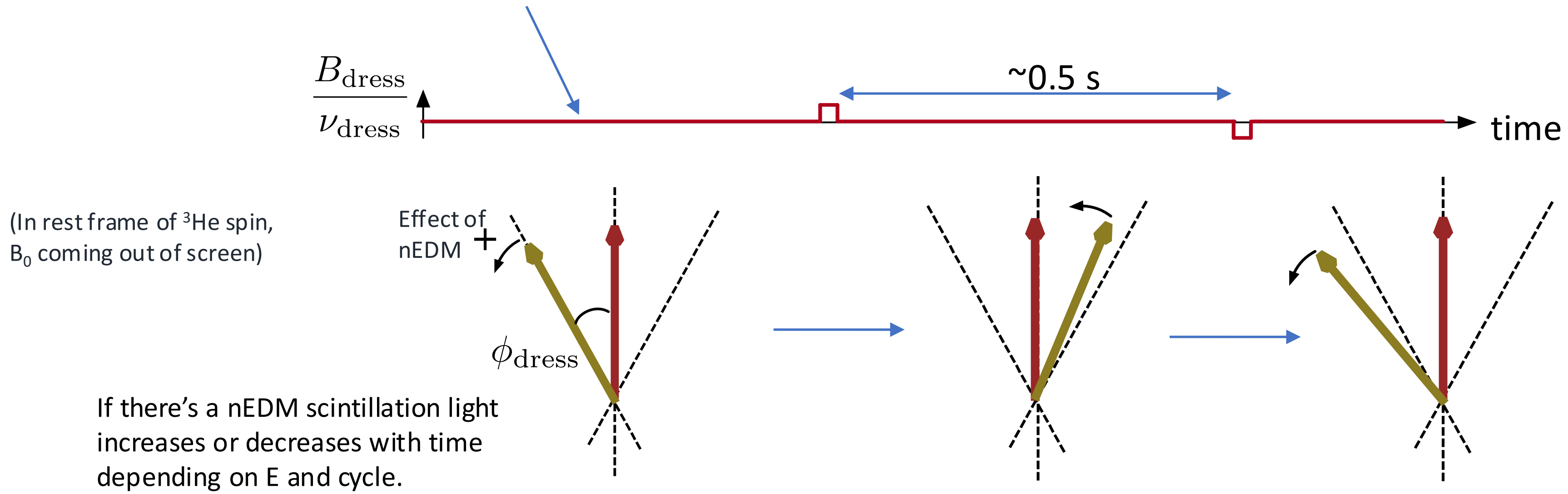

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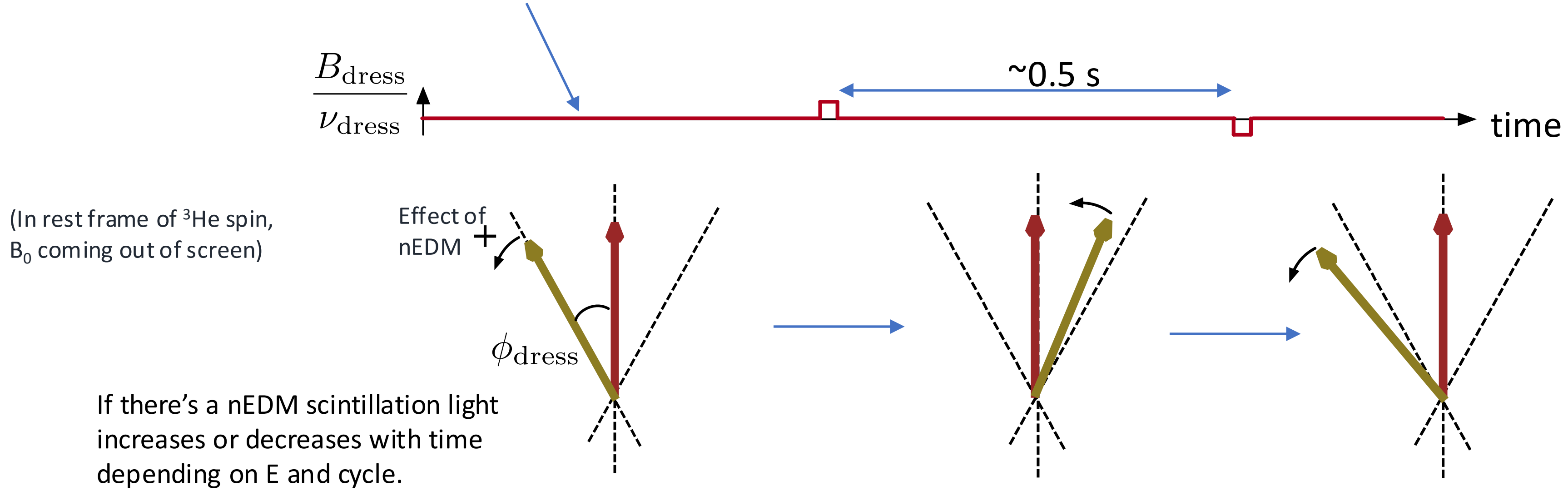


- Can treat each pair as **asymmetry measurement:** $A_d(t_i) = \frac{N_- - N_+}{N_- + N_+}$ (Ahmed et al. JINST 2019)

Predicted sensitivity: 300 live days of data (e.g. 3 years running) $\sigma(d_n) = 1.7 \times 10^{-28}\, e{\cdot}\mathrm{cm}$

- Less sensitive to static field in-homogeneities. Quality and control dressing field becomes main systematic.

nEDMSF apparatus/equipment status

Legacy Experiment Apparatus

Main subsystems

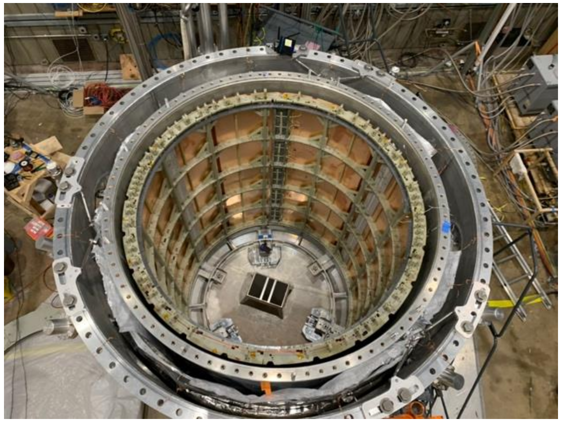
1. Superconducting magnet and shield: B_0 = 1-3 μT + flip, trim & *dressing* coils (Caltech, UK, ORNL, …)
    - Large (5 x 5 x 7 m^3) magnetically shielded enclosure
2. Central detector system: acrylic measurement cells, HV, light collection, SQUIDS (LANL, ORNL, Caltech, Montclair, …)
    - Dilution refrigerator I: ~75 mW @ 250 mK
3. Polarized ^{3}He system: atomic beam source, injection, purification (UIUC, MIT, …)
    - Dilution refrigerator II: ~75 mW @ 250 mK
4. Cryostat vessels: aluminum, composite (ORNL, …)
5. Neutron transport (UK, ORNL, …)
6. DAQ, slow controls (ORNL, …)
7. Simulation (ORNL, UK, Caltech, Montclair…)
8. Systematics and operational systems apparatus (NCSU, Caltech, Montclair …)

Hardware Status: Magnet System

B_0 $\cos\theta$ coil

Magnet system closed for cold test at ORNL

Completed magnetic shielded room at
Imedco: Hägendorf, CH



Completed B_0 coil, sc shield, vacuum chamber at
ORNL

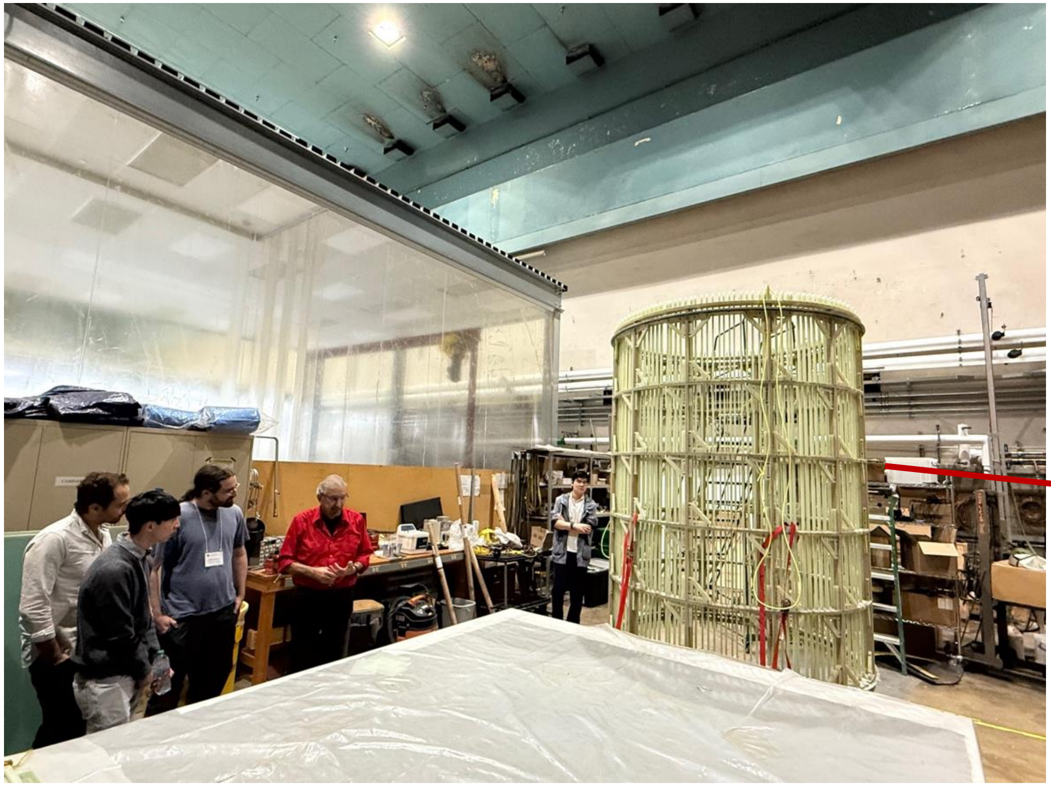
Magnet system in cold beam test
at ORNL (summer '23, '24)

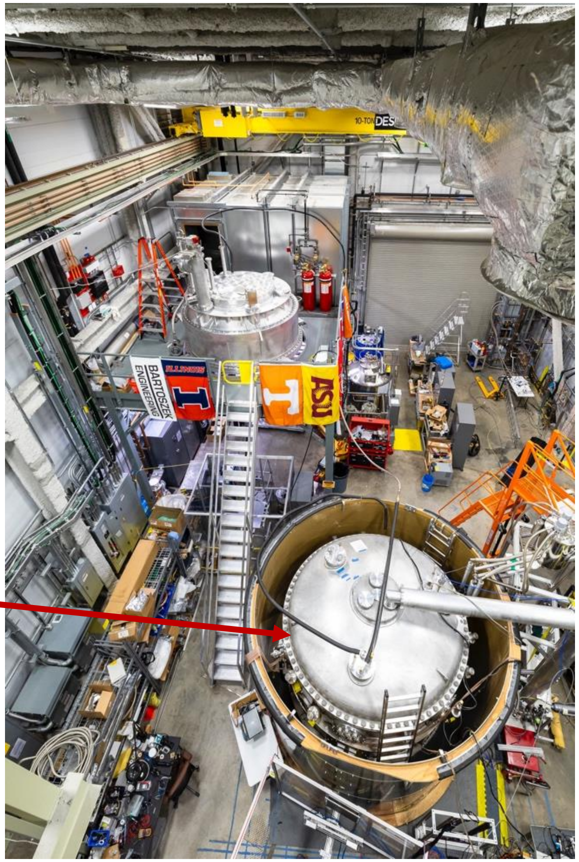
- To do: spin dressing coils

Spin-dress coil:

Oak Ridge National Lab

Brad's lab space yesterday

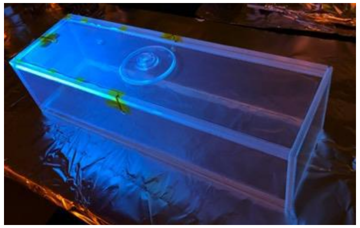




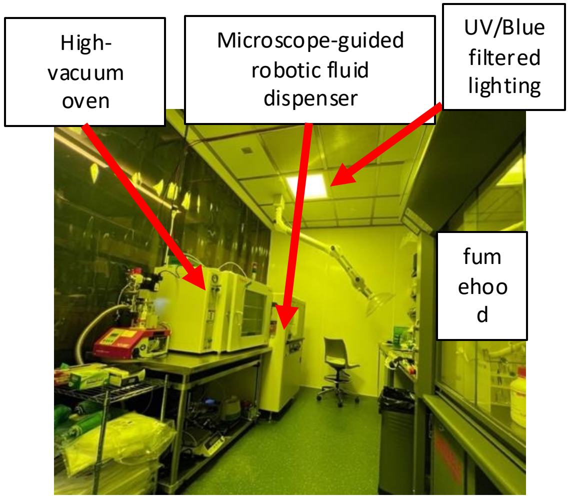
Hardware Status: Central Detector System

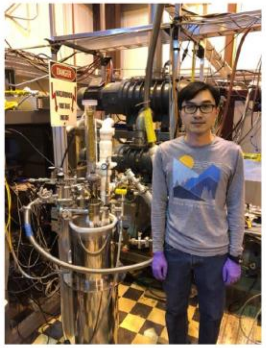
Completed cryostat top flange, tail for CDS testing

Half-scale HV test (T=0.4 K)

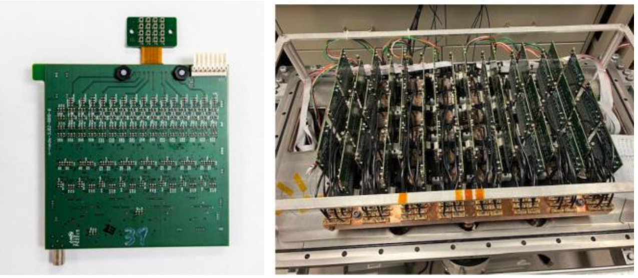


Measurement cell





Small scale HV
N. S. Phan, et al *J. Appl. Phys.* 129, 083301 (2021)



SiPM light collection

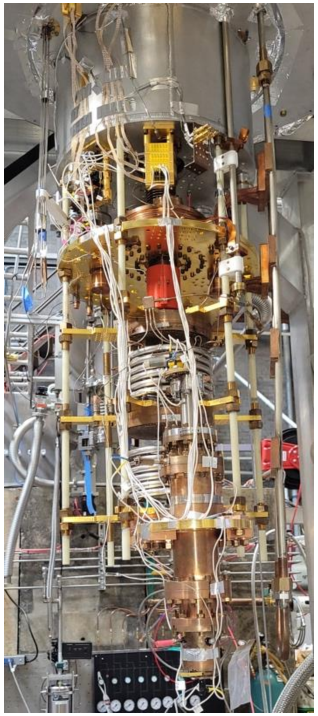
OVC composite vessel

Full-size stainless Cavallo electrodes

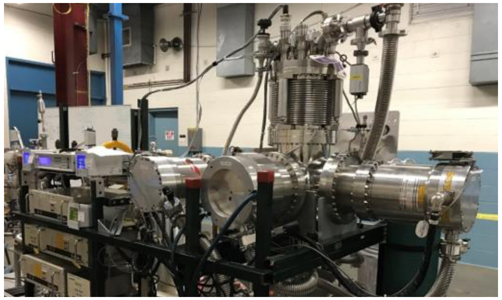
- To do: final electrode material choice & full-sized multilayered cells with thin windows

Hardware Status: Polarized ^{3}He System

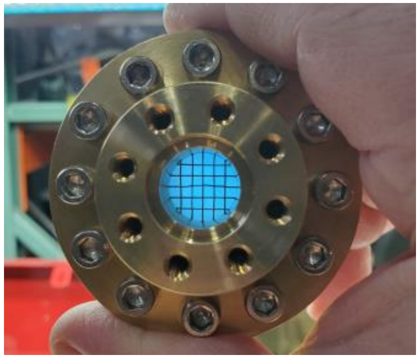
Dilution refrigerator/test cryostat



Dilution refrigerator + film burner
(75 mW at 250 mK)



Atomic beam source



Nuclepore filter: magnetic particles

- To do: injection system commissioning

Alternative physics:

Searching for axion-like particles (ALPs)
& improvement in neutron magnetic moment

time-oscillating nEDM-like signals from ALPs

- Axion-like particles couple with gluons to induce an oscillating nEDM signal [Abel et al., PRX 7 (2017)]:

$$\omega_n(t) = |\gamma_n|B_0 \pm \frac{2d_n|E|}{\hbar} + \frac{2|E|\alpha_{\rm ax}}{\hbar}\cos(\omega_{\rm ax}t + \phi_{\rm ax})$$

Amplitude of oscillation (units: e.cm)

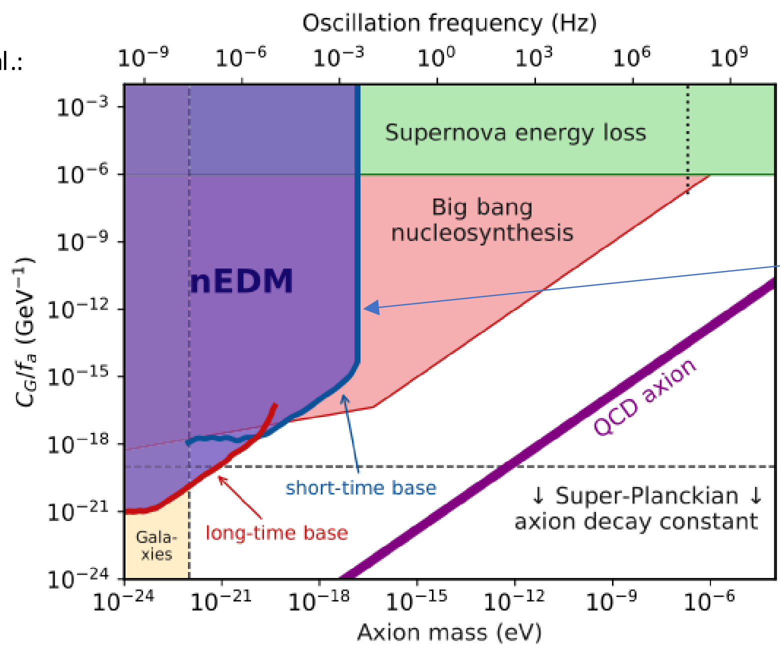
phase (free parameter in analysis)

Axion field coherently oscillates: $\omega_{\rm ax} = m_a c^2/\hbar$

axion mass

- For "standard" Ramsey UCN search technique, axion sensitivity scales with nEDM sensitivity.
- Expected ~ 2 orders-of-magnitude improvement from "standard" Ramsey UCN search technique.

From Abel et al.:



wall ~ 3mHz (300 s period)

nEDMSF's ultra-short baseline searches

- ϕ_n(t) information allows searches for oscillating-nEDM signal at frequencies higher than the measurement cycling:

In free-precession mode
(can search up to ~ 10 Hz)

$$\phi_{3n}(t) = \left[(|\gamma_3| - |\gamma_n|)B_0 \pm \frac{2d_n|E|}{\hbar}\right] t + \frac{2|E|\alpha_{\rm ax}}{\hbar\omega_{\rm ax}} \left[\sin(\omega_{\rm ax} t + \phi_{\rm ax}) - \sin\phi_{\rm ax}\right] + \phi_{3n0}$$

determines n-3He scintillation light

In dressed-spin mode: each modulation cycle can be used to extract a nEDM value. Can search up to ~ 1 Hz.

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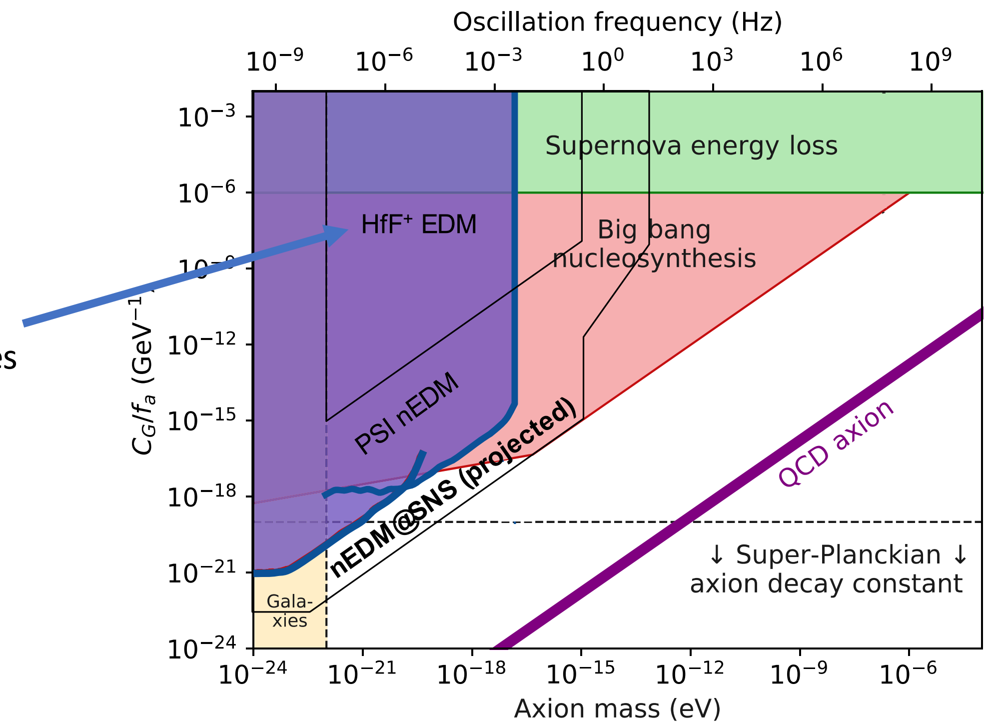
Expected axion sensitivity exclusion from nEDMSF (from signal simulations & fit):

"Experimental Constraint on Axionlike Particles **over Seven Orders of Magnitude in Mass"**

Roussy et al. PRL 2021



Measurement of γ_n/γ_{3He} to improve γ_n

- Only minor improvements in knowledge of the neutron magnetic moment over the past 5 decades

PHYSICAL REVIEW D VOLUME 20, NUMBER 9 1 NOVEMBER 1979

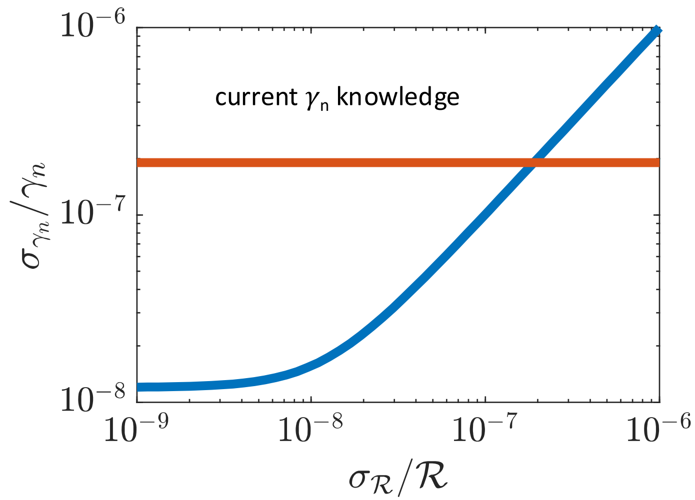
Measurement of the neutron magnetic moment

G. L. Greene* and N. F. Ramsey **+ et al.**
Harvard University, Cambridge, Massachusetts 02138

$$\frac{\sigma_{\gamma_n}}{\gamma_n} = 0.24\,\text{ppm} \quad \text{via} \quad \frac{\gamma_\text{n}}{\gamma_\text{p}} \quad \text{(Proton)}$$

Afach et al., Phys. Lett. B 739 (2014) -> $\frac{\sigma_{\gamma_n}}{\gamma_n} = 0.19\,\text{ppm}$ via $\frac{\gamma_\text{n}}{\gamma_\text{Hg}}$

$$\left(\frac{\sigma_{\gamma_n}}{\gamma_n}\right)^2 = \left(\frac{\sigma_\mathcal{R}}{\mathcal{R}}\right)^2 + \left(\frac{\sigma_{\gamma_3}}{\gamma_3}\right)^2$$



- In nEDMSF, we measure: $\mathcal{R} \equiv \frac{\gamma_n}{\gamma_\text{3He}}$ CODATA 2018: $\frac{\sigma_{\gamma\text{3He}}}{\gamma_\text{3He}} = 1.2 \times 10^{-8}$

STATISTICAL ERROR:

- 11 days: $\frac{\sigma_\mathcal{R}}{\mathcal{R}} \approx \frac{\sigma_{\omega_\text{3n}}}{\omega_\text{3n}} \lesssim 1 \times 10^{-8}\ (0.01\,\text{ppm})$ (~ 20x improvement)

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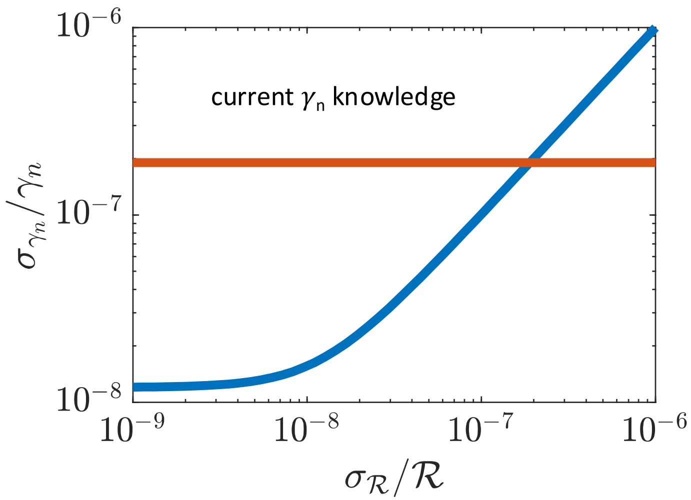

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BUT…SYSTEMATICS:

- Using comagnetometer for absolute field determination.
- UCN center-of-mass gravitational offset effect and knowledge of magnetic field gradients **very important** (need advanced magnetometry near cells)
- Does μ_3He renormalize when dissolved in superfluid ^{4}He? I don't know. The ^{3}He has an effective (inertial) mass when in superfluid.

R&D for magnetometry near nEDMSF cell

- Currently ^{3}**He comagnetometer** and **fluxgate magnetometers** ~ 0.5 m away from cell (can't run during measurements due to noise and can't place too close due to distorting fields)
- Too cold for gas based magnetometry
- Technology gap for **low-field** **AND** **low-temperature** **magnetometry**

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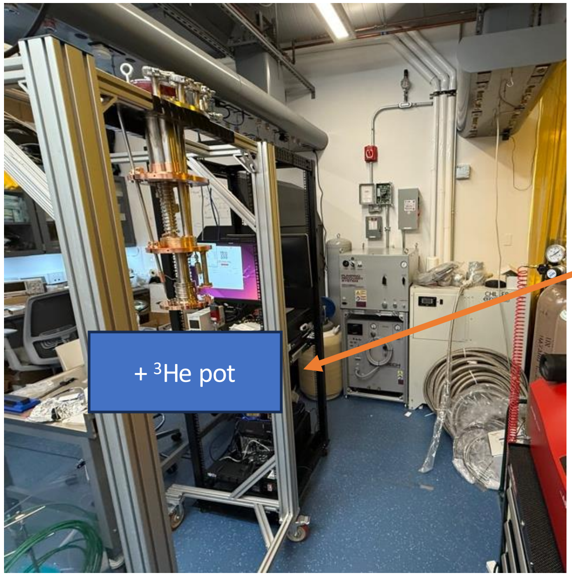
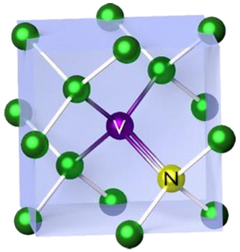
- Too cold for gas based magnetometry
- Technology gap for **<u>low-field</u> AND <u>low-temperature</u> magnetometry**
- Funding pending: development of near-cell magnetometers for nEDMSF

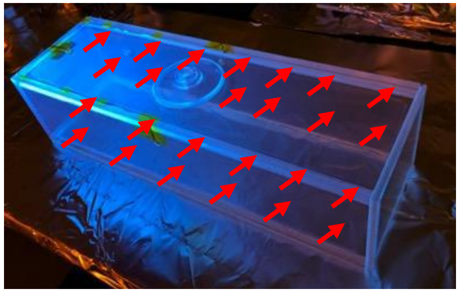
New 0.5 K platform @ Montclair



Read NV centers in diamond with SQUIDs

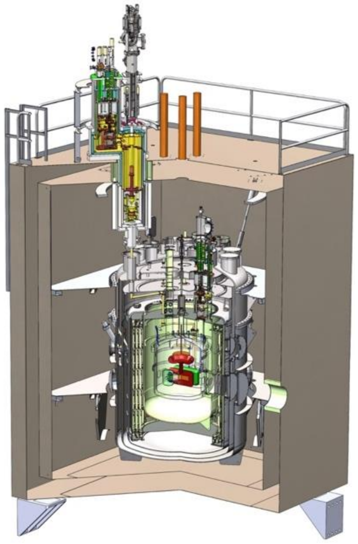


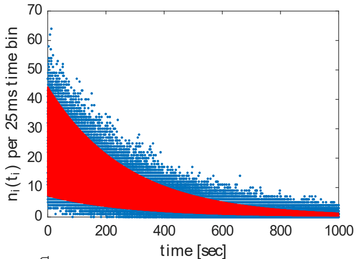
Hydrogen in plastic cell walls thermally polarized (*μB/kT*).
C.f. hospital MRI, |B|~10^6 weaker, T ~ 10^4 lower -> highly detectable (especially with SQUIDs)

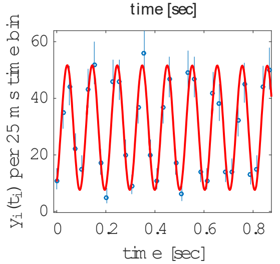


Summary

- There is a lot from the collaboration to cover, I apologize if I missed something for time's sake.
- The **cryogenic UCN + ^{3}He + superfluid** scheme offers many advantages to **reach 10^{-28} e.cm**
- In-situ produced UCN in **small cell with high-density and long storage**
- Supports high **electric field**, **SQUIDs** and **superconducting magnetic shielding**
- Can vary motion of our ^{3}He magnetometer with **small T changes to study key false EDM systematic effect**
- **Two measurement modes** with different systematic effects for **self-checking our own results**
- The live and in-situ UCN spin analysis is **a true frequency measurement**
- **New type of signals for the field**, on-going extensive work to understand its analysis
- Allows new **ultra-short baseline axion search to reach higher mass**
- **"Go east (relative to US), young man": new direction towards Europe.**

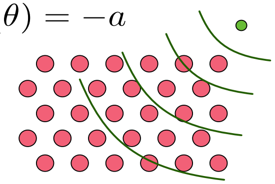






Back up slides

Ultracold neutrons (UCNs)



- Slow neutrons undergo **scattering** from a nuclei via strong force: $\psi(\mathbf{r}) \propto \exp(i\mathbf{k}\cdot\mathbf{r}) + f(\theta)\frac{\exp(ikr)}{r}$ → s-wave: $f(\theta) = -a$
- Coherent scattering off collection of nuclei: $\psi(\mathbf{r}) = \exp(i\mathbf{k}_0\cdot\mathbf{r}) - \int \beta(\mathbf{r}')\,\psi(\mathbf{r}')\frac{\exp(ik_0|\mathbf{r}-\mathbf{r}'|)}{|\mathbf{r}-\mathbf{r}'|}\mathrm{d}^3r'$
- Apply Born approximation, where nuclei can be treated as δ-functions (nuclei size ~ 1 fm, where as slow neutron λ > 1 Å)
- Volume average gives **effective neutron "optical" potential:**

$$V_{\text{opt}} = \frac{2\pi\hbar^2}{m}\sum_i n_i b_i$$

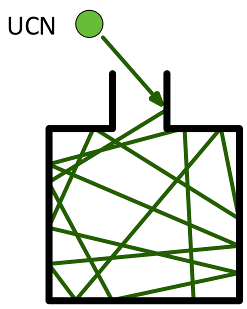
- n_i: nuclei-number density
- b_i: bound coherent scattering length $b = \frac{m_n}{m}a$
- $\sum_i$: sum over nuclear species in a material

Material	V_{opt}
^{58}Ni	335 neV
Be	252 neV
Fluorocarbons	~100 neV
Al	54 neV
polyethylene	-9 neV
d8-polystyrene	160 neV

Idea: Fermi (1946); Published: Zeldovich (1959);
Realization: Shapiro et al., Dubna (1968) & Steyerl et al., Munich, (1969)

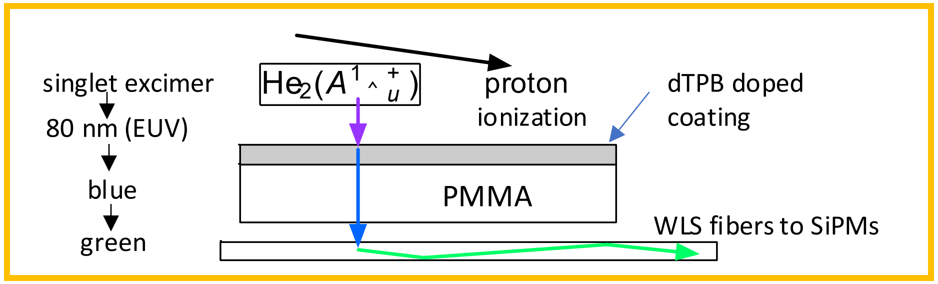
> If **energy below V_{opt} of a material** => **total *external* reflection at all incident angles**
> => **<u>Ultracold neutrons</u>** can be **stored in a material "bottle"**

$$E \lesssim 300\,\text{neV}, \lambda \gtrsim 60\,\text{nm}, v \lesssim 7\,\text{m/s}, \text{"temperature"} \lesssim 2\,\text{mK}$$



- **Typically 10^{-4} loss probability per reflection** $\Rightarrow R_{\text{reflect}} \approx (vA_{\text{walls}})/(4\times\text{Volume})$
- Store UCNs with time constant (including β-decay loss) $\tau_{\text{tot}} \lesssim$ 100 - 600 s

Superfluid helium as a scintillator



- **Light signal gives live angle of neutron spin relative to ^{3}He spin!**
  - **UCNs produced and spin analyzed in the cell** (i.e. no transport loss)
  - ~ 100% detection efficiency
  - more photo-electrons (PE) = better discrimination against backgrounds
  - Suppression of EUV in electric field: Ito et al. PRA (2012)

Light collection efficiency test apparatus @ ORNL with β-source. Projected > 19 PE in final setup

The pseudomagnetic field

- The neutron & ^{3}He scattering length is spin-dependent
- Recall:

$$V_{\rm opt} = \frac{2\pi\hbar^2}{m}\sum_i n_i b_i$$

number density

bound coherent scattering length $b = \frac{m_n}{m}a$

sum over nuclear species in a material

- So the optical potential the UCNs are in becomes:

$$V_{\rm opt,tot} = V_{{\rm opt},{}^4{\rm He}} + V_{{\rm opt},{}^3{\rm He}}$$

$V_{{\rm opt},{}^4{\rm He}}$: 18.5 neV

$V_{{\rm opt},{}^3{\rm He}}$: $10^{-9}\,{\rm neV} + {\rm const}\,(S_3 \cdot S_n)$ (for $x_3 \sim 10^{-10}$)

- Recall: $V_{\rm mag} \sim \mu \cdot B$

so this effect is like a magnetic field ("pseudomagnetic field")

$$\vec{H}_{\rm pseudo} = -\frac{4\pi\hbar}{m_n\gamma_n}\rho_3 b_i' \sqrt{\frac{I}{I+1}}\vec{P}_3$$

$\sim 0.1\,\mu$G ($\sim$ 10 pT) (for $x_3 \sim 10^{-10}$, $P_3 \sim 1$)

^{3}He density

Incoherent n-^{3}He scattering length

The pseudomagnetic field

- The neutron & ^{3}He scattering length is spin-dependent
- Recall:

$$V_{\rm opt} = \frac{2\pi\hbar^2}{m}\sum_i n_i b_i$$

number density (n_i)

bound coherent scattering length (b_i): $b = \frac{m_n}{m} a$

sum over nuclear species in a material ($\sum_i$)

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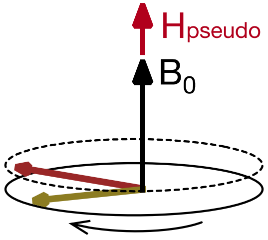
ρ_3: ^{3}He density

b_i': Incoherent n-^{3}He scattering length

$\sim 0.1\ \mu$G (~ 10 pT) (for $x_3 \sim 10^{-10}$, $P_3 \sim 1$)



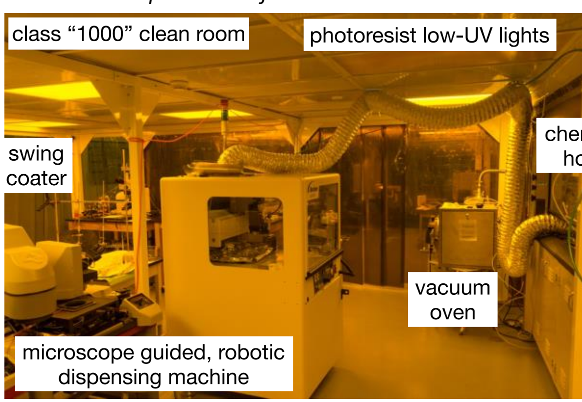
- ^{3}He does not see a pseudomagnetic field from UCNs
- After $\pi/2$ pulse, need ^{3}He spin accurately in perpendicular plane
- Since there are two cells, any frequency drifts cancel out
- Can add statistical noise between measurements though
- Once in perp. plane, frequency shifts are small because it's a Bloch-Siegert shift

Measurement cells

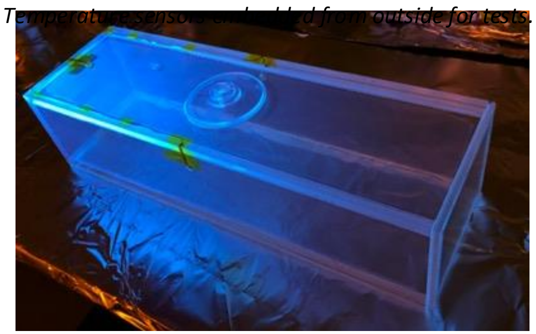
- Dimensions optimized for statistics and systematics. (e.g. E-field, diffusion-limit L^{-4} dependence of T_2 time & L^2 dependence of false EDM, magnetic field gradients, etc.).
- Cells separate from electrodes (cooling needed for heat flush)

Inner coating	~ 1 um thick d-TPB embedded in d-PS matrix	Non-magnetic and not electrically conductive. Deuteration for high Fermi potential (165 neV from neutron reflectometry). TPB for detection of 80 nm ^{4}He scintillation light (see Ito, Cianciolo, Loomis talks)
Side walls	~ 1 cm thick p-PMMA plates	Optical photon transmission, mechanical strength, and purity. "Swing coating" on flat plates produce surface finish ~ 5 nm RMS roughness (AFM measured)
End windows	~ 5 mm thick d-PMMA	reduce activation caused by scattering of 9 Å beam
Sealed cell	deuterated solvent cemented	to separate 10^{-10} polarized ^{3}He inside cell from unpolarized natural-abundance ^{3}He
Cell hole	~ 1 cm opening	initial 4He filling then loading/unloading 3He via heat flush. Low UCN loss.

Cell production facilities in clean room



Full-sized test measurement cell (illuminated by 360 nm UV lamp). Temperature sensors embedded from outside for tests.



*p- & d- refers to "protonated" or fully-deuterated versions of a material.

PMMA = poly(methyl methacrylate), more commonly-known by tradenames acrylic or plexiglass.

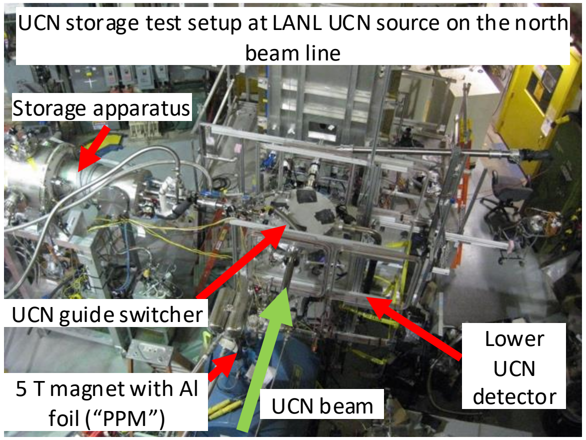
PS = polystyrene.

TPB = tetraphenyl butadiene, an electroluminescent dye

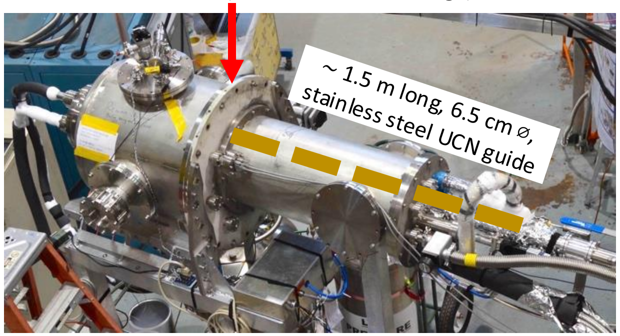
Cryogenic UCN storage tests with external UCN source

Thanks to collaborators: Cianciolo, Clayton, Cooper, Curie, Golub, Griffith, Huffman, Ito, Korobkina, Makela, McDonald, O'Shaughnessy, Pentilla, Ramsey, Smith, Stanislaus, Tang, Weaver, Wei

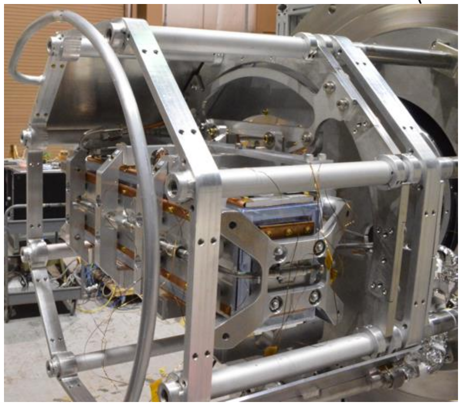
- A **cryogenic UCN storage apparatus** used with the **Los Alamos National Lab. solid-D_2 UCN source**.
- **Standard fill-and-empty setup** with cell valve & UCN guide switcher to connect (1) UCN source to cell or (2) cell to lower UCN detector
- **Cells cooled by spring-loaded cooling plates coupled to flowing L^4He line**. Cells reach nominal 30 K in ~ 3 days (but can reach 15 K with high L^4He rate).
- Dry & clean vacuum system: in vacuum outside cell, P ~ 5 x 10^{-7} mbar before starting to cool cell. Outgassing dominated by plastic.
- Pumping inside cell restricted due to 1-cm cell hole & UCN guides. Put UCN guide switcher in "intermediate" position for increased cell pumping speed.
- **Cells are heated** to 50 degC (coating limit) and **pumped for 10-14 days** before cooling.
- The input L4He flow is split, **a region of stainless steel UCN guide ~20 cm away from the cell is maintained to be coldest point in the system** (nominally > 20 K colder than cell). This SS surface **acts as a cryopump** for pumping out cell and **traps condensable-contamination** from reaching inside cell.



Slide-openable vacuum vessel with flowing LN_2 radiation shield (80 K & ~ 3π sr coverage)



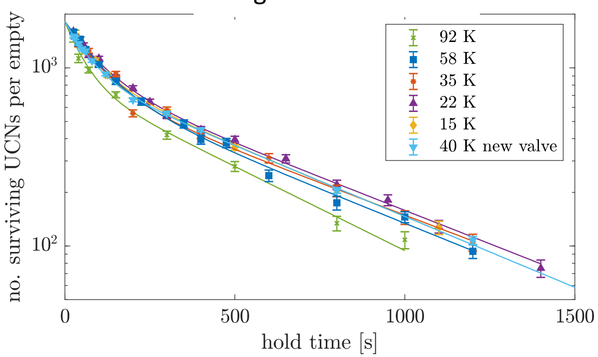
Spring loaded cooling plates used to maintain contact with cell
Return L4He cools another radiation shield (50 K)



UCN storage results

(Data normalized so number of UCNs at t=0 extrapolated with double exponential fit are matched. The value chosen at t=0 is average of the different storage curves with same cell, measured over consecutive days)

2nd generation cell #2

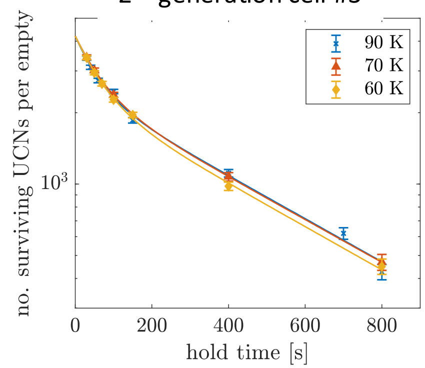


- Beam position: behind UCNτ
- Measured with old and new valve systems

Fitting 40 K data:

N_{short} = (50 ± 2) % , τ_{short} = (73 ± 7) s
N_{long} = (50 ± 2) %, τ_{long} = (546 ± 16) s

2nd generation cell #3

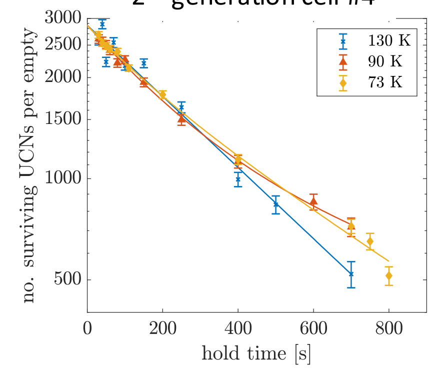


- Beam position: north beam line
- dPMMA valve system

Fitting 60 K data:

N_{short} = (45 ± 4) % , τ_{short} = (66 ± 16) s
N_{long} = (55 ± 4) %, τ_{long} = (477 ± 47) s

2nd generation cell #4



- Beam position: north beam line
- dPMMA valve system
- Reduced dust contamination during cell production

Fitting 73 K data:

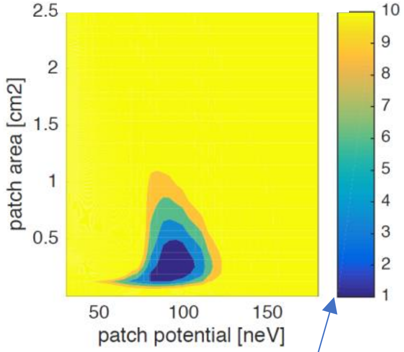
N_{short} = (24 ± 28) % , τ_{short} = (170 ± 190) s
N_{long} = (76 ± 28) %, τ_{long} = (590 ± 190) s
OR
$\tau_{single\text{-}exp}$ = (490 ± 11) s

- Either sum of two exponential decays ("long" and "short") or single-exponential fit.
- When sum of two exp decays, strong correlations between fitted parameters
- When cell not cooled, $\tau_{single\text{-}exp}$ = (130 ± 5) s
- Storage times here are β-decay + cell wall losses

Interpretation of results

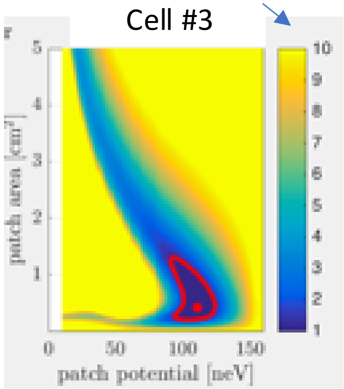
- High quality set of cryogenic UCN storage data with a new type of deuterated polymer coated surface (V_F = 165 neV, fluorescent, ^{3}He polarization friendly) exhibiting excellent UCN storage properties. Cell #4 with $\tau_{single\text{-}exp}$ = (490 ± 11) s => **loss per reflection ~ 2 x 10^{-5}**
- **Standard UCN-energy-dependent wall loss theory** (i.e. f = W/V_F description) **insufficient** for describing data exhibiting **strong double-exponential decay**.
- From crude information on UCN spectrum, we deduce it is the higher-energy UCNs in the τ_{short} component. Commonly explained away by above-trapping threshold UCNs but the time scales here are very long for our rectangular cells.
- Most promising **model found so far has been fitting with a small area "patch"** (~ 0.3 cm^2) with **low V_F** (~ 100 neV) exposed to UCNs
- Patch parameters very similar between cells #2 & #3
- Possible theories for cell #4:
  - (1) τ_{short} component very short, so not visible since shortest hold time is 25 sec (patch area > 3x larger)
  - (2) τ_{short} component very long or non-existent (difficult to fit for. Would need patch 5x smaller)
  - (3) higher UCN energies not loaded into the cell in the first place.
- Currently developing UCN tracking simulations to increase understanding. Possibly use UCN spectrometer in future experiments.

Cell #2



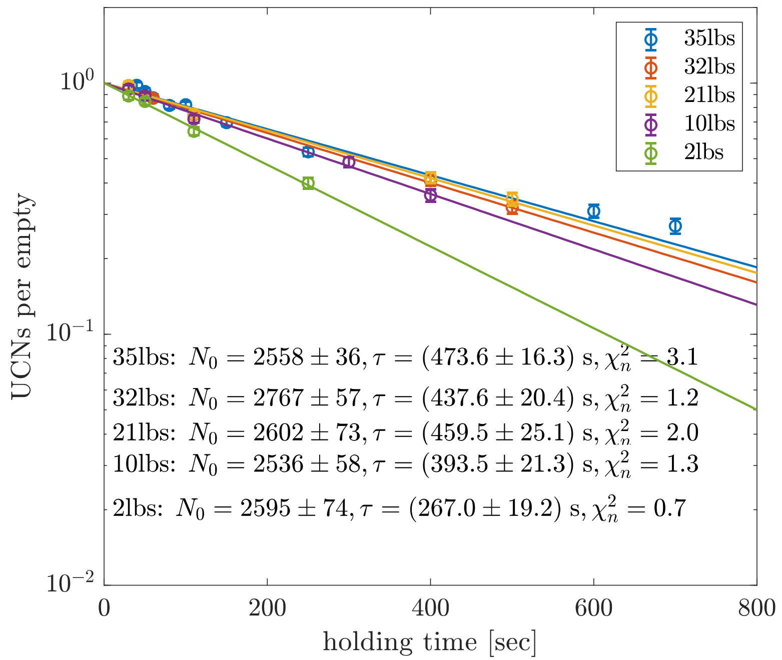
χ^2/dof contours

Cell #3



dPMMA UCN cell valve results

- These results show we have **learned to implement a UCN valve with negligible UCN loss**
- The leak tightness of the valve is more stringent for containing ^{3}He inside the cell in final experiment (v ~ 30 m/s)



9 Å neutron beam induced cell activation in final experiment

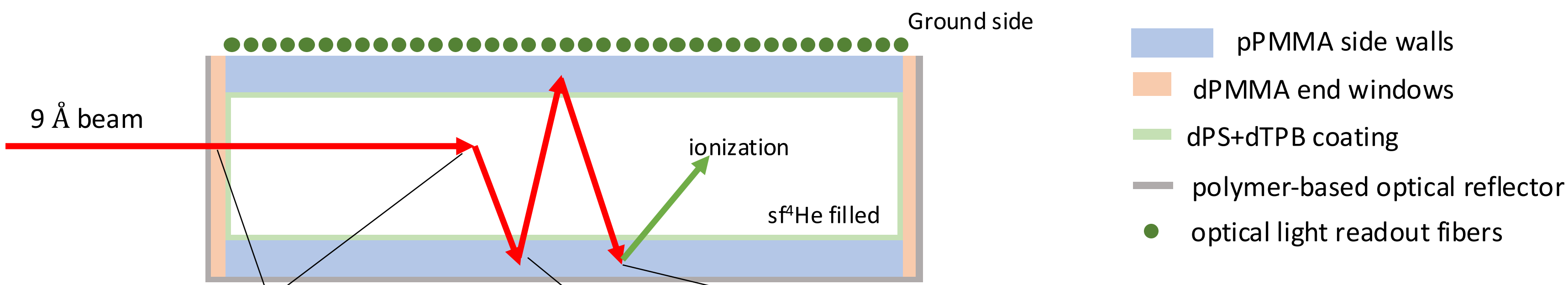
- In-situ UCN production via super-thermal production in sf^{4}He by 9 Å beam (via choppers) offers many advantages:

High UCN density ~ 150 UCN/cm^3 after 1000 s of "filling time"

No UCN or depolarization loss from transport

Spatial spread of beam and filling time reduces phase-space evolution at start of precession measurements

- The beam intensity is 5 x 10^5 s^{-1} in each cell (UCN production P = 0.31 UCN/cm^3/s), so T_{fill} = 1000 s -> 5 x 10^5 neutrons incident



Scattering in sf4He (coherent inelastic scattering).
Mean-free-path = 20 m, 40 cm cell, 2%.
OR
Scattering in dPMMA windows (mix coherent elastic scattering & incoherent elastic scattering). ~ 1% depending on window thickness
OR
Direct activation of impurities in dPMMA with decay chains

Cold neutrons bounce around via incoherent elastic off ^{1}H

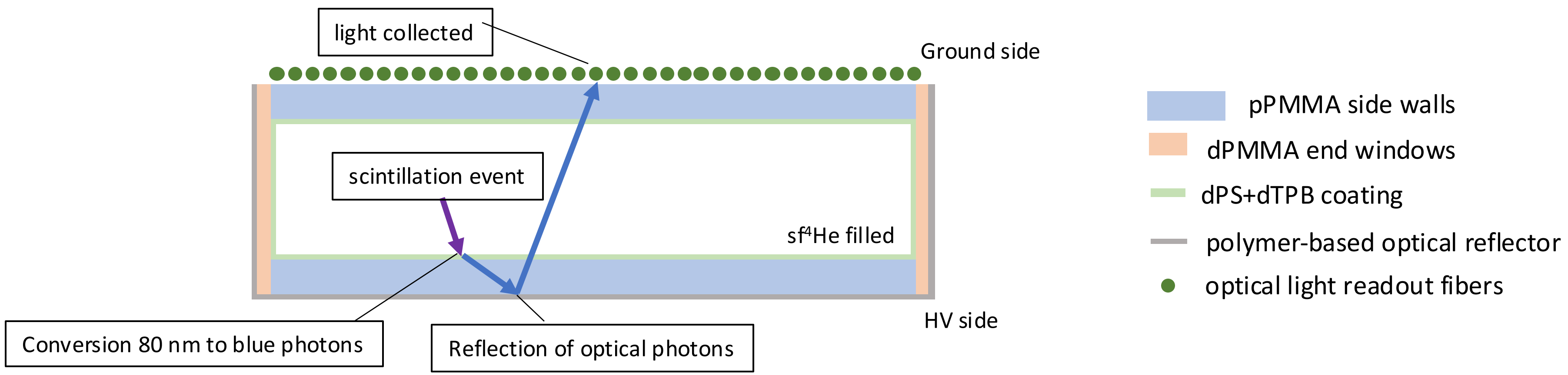
Eventually n+p -> D + γ (2.2 MeV) + other prompt-reactions => can produce free charge in cell
OR
n + contaminant -> short or long lived decay chain => delayed background scintillation events

(see Korsch & Loomis talks)

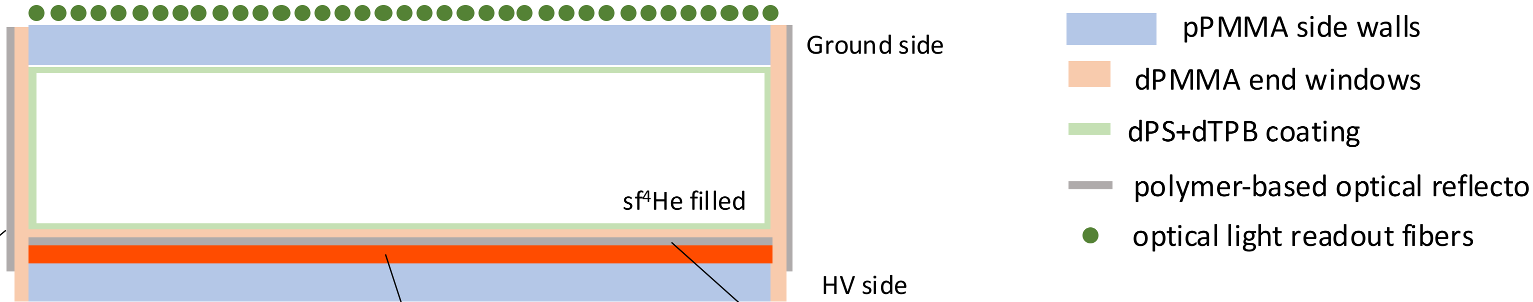
Note: we developed L^{4}He MCNP neutron scattering kernels to 4 K. (Thanks to C. Lavelle from Johns Hopkins!)

How scintillation light is collected in measurement cell

(see Cianciolo talk)



Solution to problem

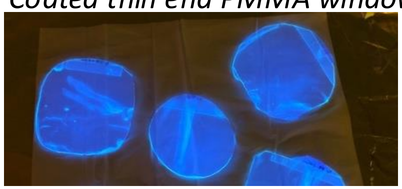


Make dPMMA end windows thin (~ 0.5 - 1 mm) & very pure

Embed ^{6}Li cold neutron absorbing layer (1-2mm thick) close to inside of cell (but UCNs can't reach)

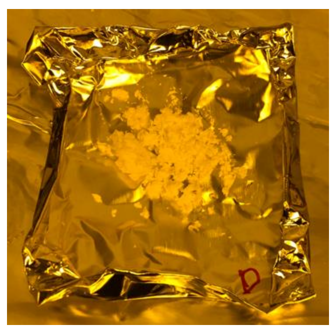
Place optical reflector between dPS+dTPB coating and (non-optically transparent) n-absorbing layer

Coated thin end PMMA windows

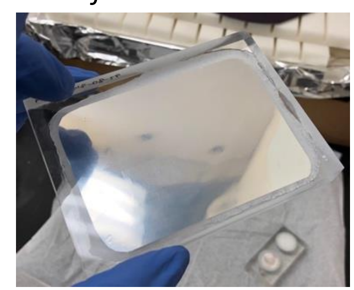


LN2 dunk and strength tests

In-house synthesis of high-purity dPMMA



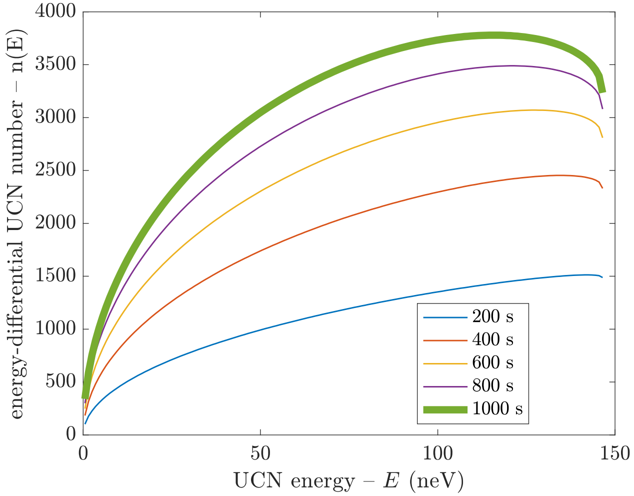
1/3rd scale prototype side wall with embedded LiOH absorber and optical reflector



Evolution of UCN spectrum during filling and precession

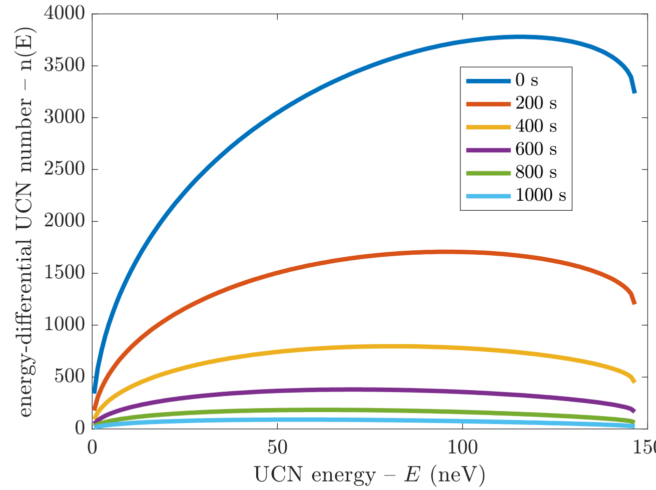
Example: used f = W/V = 0.8 x 10^{-5}

UCN spectrum during “filling” (low ^{3}He absorption)



Statistically optimized T_{fill} = 1000 s:

UCN spectrum evolution during free precession measurement time (includes τ_3 = 500 s)



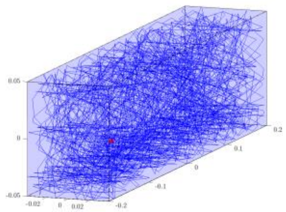
- Produced **UCN spectrum in sf^{4}He is well-described**. Transport in guides not so much.
- Above assumes mechanical equilibrium. **Phase-space evolution will be small in nEDM@SNS** (3 L cell, with UCNs produced with approximately isotropic momentum and close to uniformly throughout cell, filled over 1000 s). Next step is to confirm with simulations
- These are the UCN spectra inside the cell. **Since spin analysis is in-situ, no need to correct for UCN-energy dependent transport loss** (and depolarization loss) during transport to interpret any UCN spectral measurements
- Change filling time (with reduction on statistics) to change initial UCN spectrum slightly for systematics

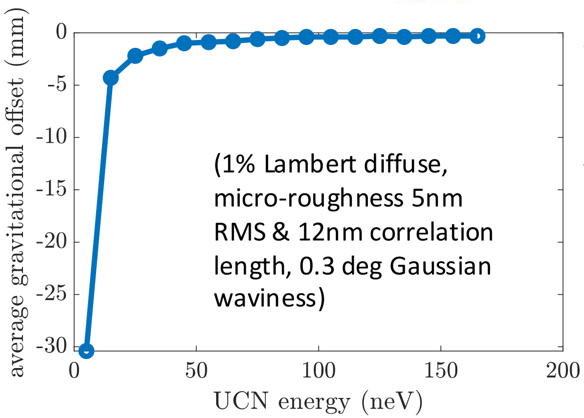
Use time-evolution of UCN gravitational offset to study UCN spectrum

UCN tracking simulations:

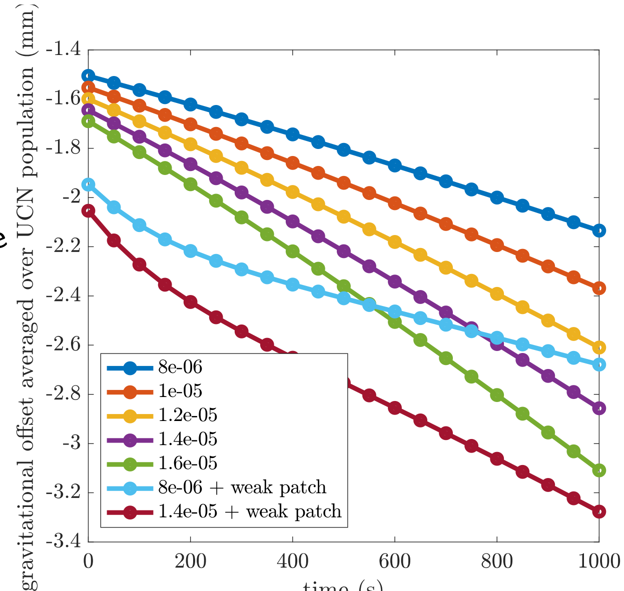
Shown E = 100 neV

Straight lines between wall collisions displayed.





Combine with UCN spectral evolution from previous slide



UCN center-of-mass offset when averaged over UCN population

$$f_n = \frac{\gamma_n}{2\pi}\left(B_0 + \frac{d|B|}{dz} h_{\text{off}}(t)\right)$$

Vertical gradient

$(B_0 \rightarrow \text{from } ^3\text{He})$

- Apply **known gradient, measure $f_n(t)$** to **get information on the time-evolution of average UCN energy** during precession.
- **Combine with total number UCN storage time measurement**: just watch β-decay without loading ^{3}He.
- More direct than spin-echo since since measuring precession frequency
- Phase-space evolution (which will impact this systematic effect as well as others!) less in the nEDM@SNS experiment
- A good chance for controlling this important systematic effect! Currently in early days of development still.

Photoelectron spectrum