”Who wants neutrons?”

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Ecole de Physique des Houches does!

Beyond Ramsey: nEDM techniques with Superfluid ^{4}He for reaching 10^{-28} e.cm

Ecole de Physique des Houches does!

Kent Leung, EDMs2016: WE-Heraeus Workshop

Les Houches, France, March 03, 2026

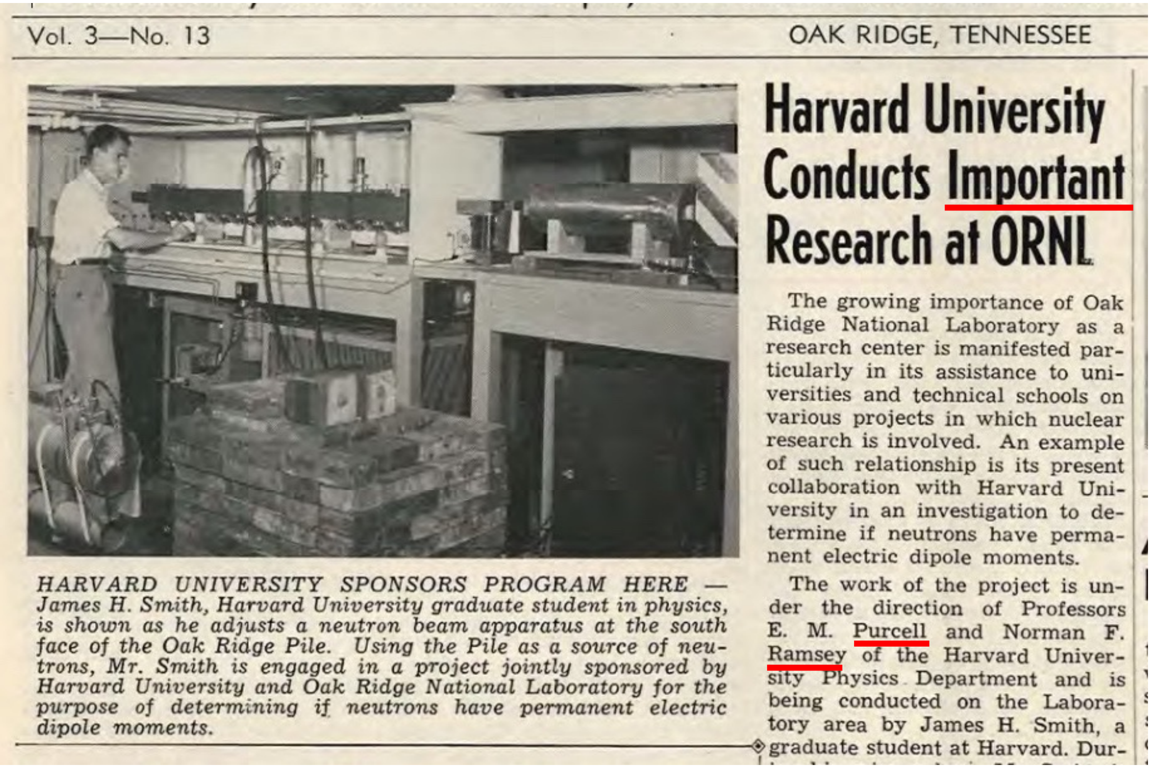
“In the sciences of observation, the work of the observer consists in making experiments, and in observing the results; but his/her **skill is shown in the selection of the experiments, and in the estimation of the accuracy of the results.**”

— James Clerk Maxwell, “On the Elementary Relations between Electrical Measurements,” *Philosophical Magazine* (1861).

“The history of science teaches only too plainly the lesson that **no single method is absolutely to be relied upon**, that **sources of error lurk where they are least expected**, and that they **may escape the notice of the most experienced and conscientious worker**.”

— Sir John William Strutt, 3rd Baron Rayleigh, *Report of the British Association for the Advancement of Science* (1883).

Where the EDM field started?



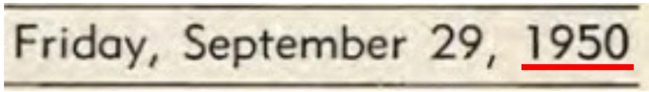
Vol. 3—No. 13 OAK RIDGE, TENNESSEE

Harvard University Conducts Important Research at ORNL

HARVARD UNIVERSITY SPONSORS PROGRAM HERE — James H. Smith, Harvard University graduate student in physics, is shown as he adjusts a neutron beam apparatus at the south face of the Oak Ridge Pile. Using the Pile as a source of neutrons, Mr. Smith is engaged in a project jointly sponsored by Harvard University and Oak Ridge National Laboratory for the purpose of determining if neutrons have permanent electric dipole moments.

The growing importance of Oak Ridge National Laboratory as a research center is manifested particularly in its assistance to universities and technical schools on various projects in which nuclear research is involved. An example of such relationship is its present collaboration with Harvard University in an investigation to determine if neutrons have permanent electric dipole moments.

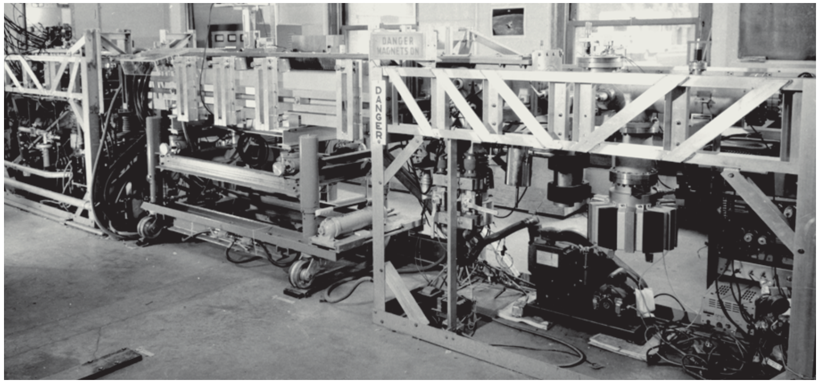
The work of the project is under the direction of Professors E. M. Purcell and Norman F. Ramsey of the Harvard University Physics Department and is being conducted on the Laboratory area by James H. Smith, a graduate student at Harvard. Dur-

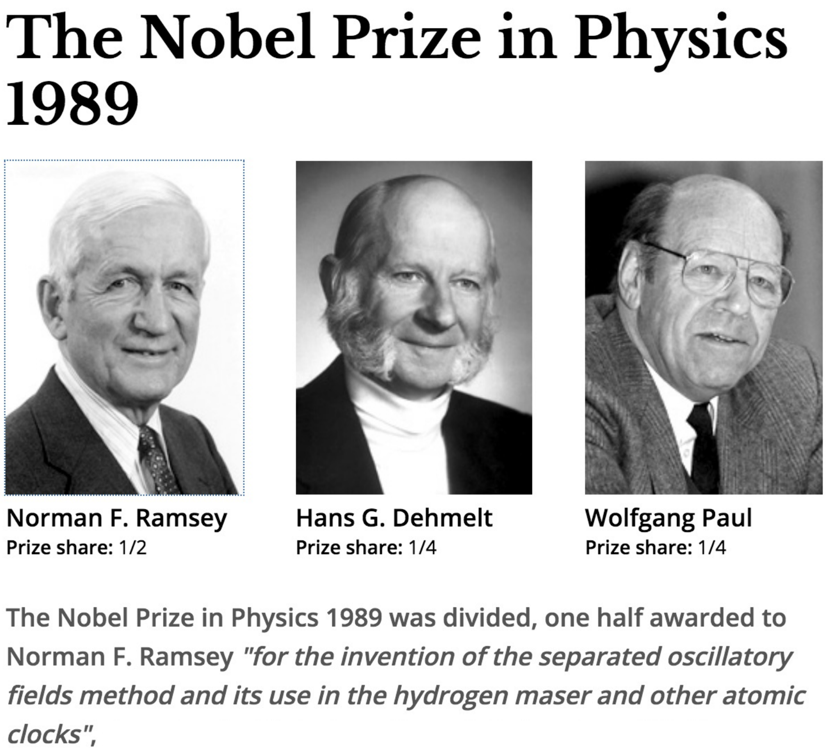


Friday, September 29, 1950

- Oak Ridge National Laboratory's X-10 pile went critical in 1943, and civilian research began in 1945.
- Wu & Ambler's P-violation experiment in 1957
- nEDM Result published in 1957 by *Smith, Purcell & Ramsey:* $D=(-0.1\pm2.4)\times10^{-20}$ cm,

Ramsey’s method of separated oscillatory fields





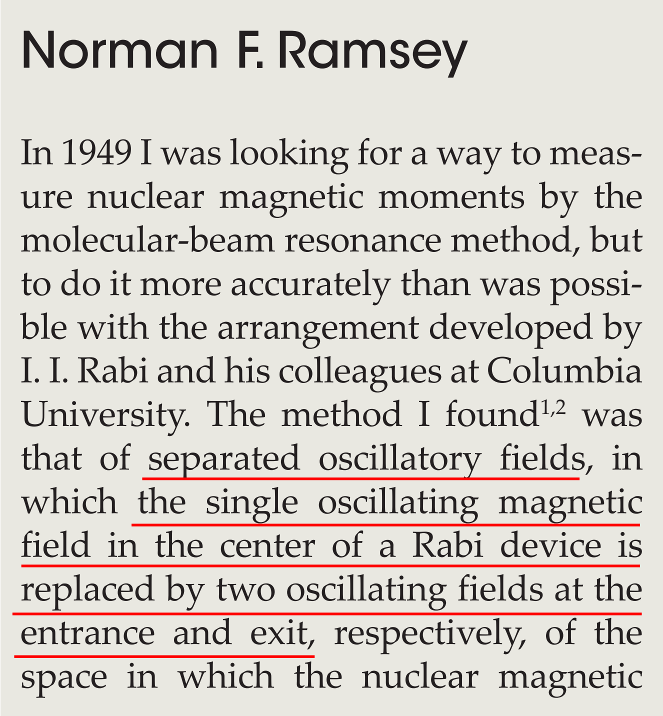
The Nobel Prize in Physics 1989

Norman F. Ramsey
Prize share: 1/2

Hans G. Dehmelt
Prize share: 1/4

Wolfgang Paul
Prize share: 1/4

The Nobel Prize in Physics 1989 was divided, one half awarded to Norman F. Ramsey *"for the invention of the separated oscillatory fields method and its use in the hydrogen maser and other atomic clocks"*,



Norman F. Ramsey

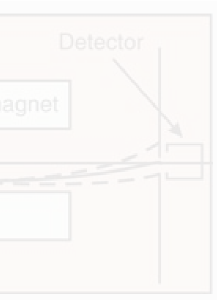
In 1949 I was looking for a way to measure nuclear magnetic moments by the molecular-beam resonance method, but to do it more accurately than was possible with the arrangement developed by I. I. Rabi and his colleagues at Columbia University. The method I found[1,2] was that of separated oscillatory fields, in which the single oscillating magnetic field in the center of a Rabi device is replaced by two oscillating fields at the entrance and exit, respectively, of the space in which the nuclear magnetic

Advice from Rabi

The first advice I received from Rabi in 1937 when I applied to him to begin my research was that I should not go into the field of molecular beams since the interesting problems amenable to that technique had already been solved and there was little future to the field. I have often wondered how I . . . had the temerity to disregard this bit of advice from the master. However, I

(Quoted from Norman Ramsey's contribution to *A Tribute to Professor I. I. Rabi*, Columbia University, New York, 1970.)

Rabi's method



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Ramsey

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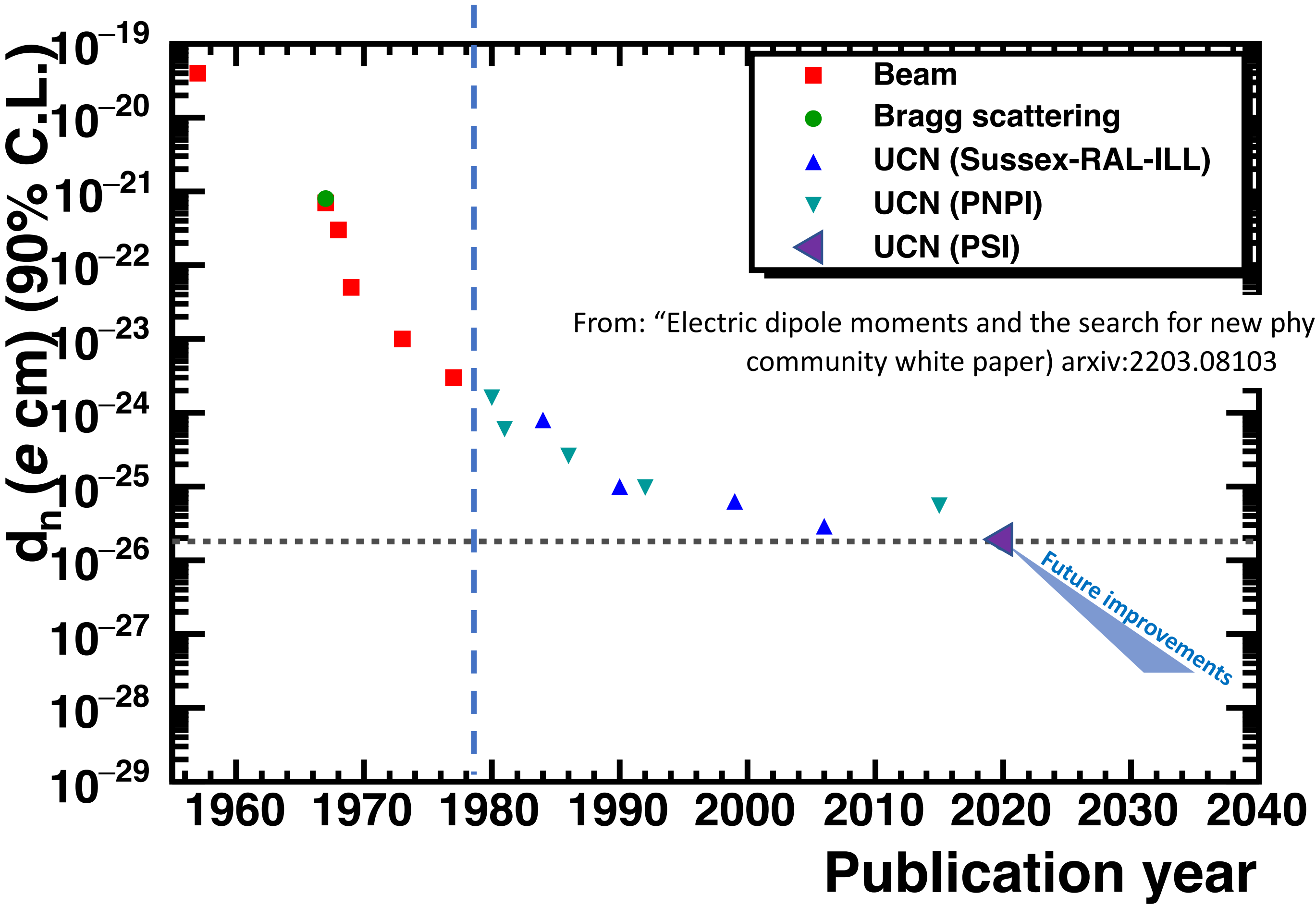
space in which the nuclear magnetic

Neutron EDM historical sensitivity

(High numbers/rates; short interaction/useful time)

(Low numbers/rates; long interaction/useful time)

Cold neutron beam era → ultracold neutrons era (but kept Ramsey's method)

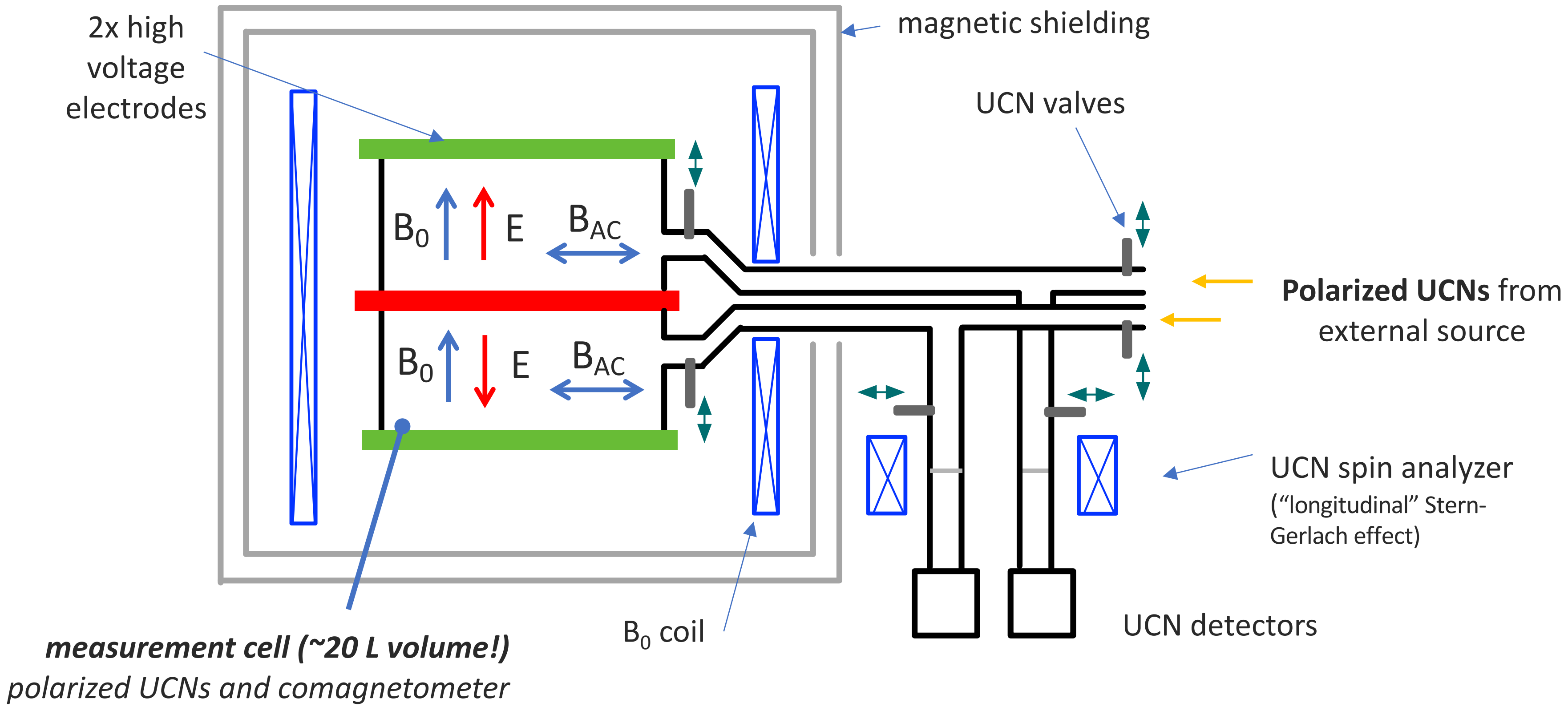


From: "Electric dipole moments and the search for new physics" (2022 community white paper) arxiv:2203.08103

Experimental techniques with neutrons restricted by: neutral & no electronic states.

(Excited Δ state ~ 200 MeV away…)

Standard Ramsey technique with UCNs



- At the **end of free precession**, neutron population's **final phase** measured by counting number of spin down N_{down} (or N_{up}). For UCNs, spin analysis typically done ***ex-situ*** for UCNs measurements). A full cycle takes 200-300s.
- Repeat cycle ~ 4x to extract a frequency in a cell
- Reverse E-field or, better, the "super ratio"

$$S = \frac{f_{\mathrm{cell1}}^{\mathrm{HV}\uparrow} f_{\mathrm{cell2}}^{\mathrm{HV}\downarrow}}{f_{\mathrm{cell1}}^{\mathrm{HV}\downarrow} f_{\mathrm{cell2}}^{\mathrm{HV}\uparrow}}$$

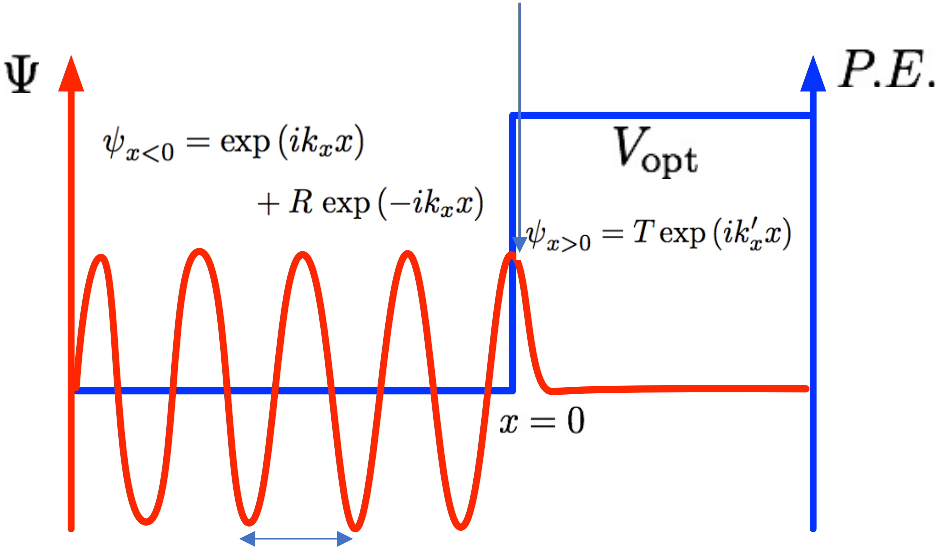
“Ultracold Neutrons are Kitchen”

- L. N. Bondarenko, Kurchatov Institute

Transporting, especially polarized UCNs, can be tricky! Loss mechanisms not fully understood.

$$W = \frac{\hbar}{2}\sum_i n_i \sigma_{\text{loss}}(v) v$$

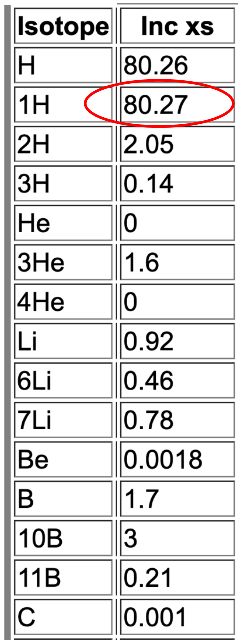
$$U = V_{\text{opt}} + iW$$



λ ~ 100 nm

Theoretical loss ~ 10^{-5} per reflection.
But typically observe several 10^{-4}.

Neutron incoherent scattering cross-section



Isotope	Inc xs
H	80.26
1H	80.27
2H	2.05
3H	0.14
He	0
3He	1.6
4He	0
Li	0.92
6Li	0.46
7Li	0.78
Be	0.0018
B	1.7
10B	3
11B	0.21
C	0.001

- Hydrogen is everywhere! Especially on surfaces (and diffuses into materials).
- Depolarization losses could be magnetic impurities on surface.

“Ultracold Neutrons are Kitchen”

- L. N. Bondarenko, Kurchatov Institute

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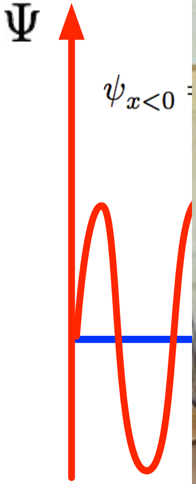



My kitchen after I cook

urfaces
(and diffuses into materials).

- Depolarization losses could be magnetic impurities on surface.

Theoretical loss ~ 10^{-5} per reflection.
But typically observe several 10^{-4}.

Sensitivity

Comes from the uncertainty principle: $\Delta E\,\Delta t \geq \hbar/2$

(often greater!)

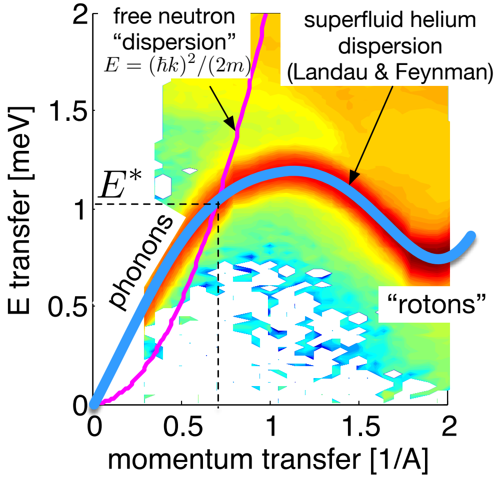
Get the "shot noise" **limit:** $$\sigma(d_n) \geq \frac{\hbar}{2\alpha E T\sqrt{N}}$$

α = polarization contrast	$\sim$ 80 % → 95% if UCN spin analysis done in-situ
***E* = electric field strength**	$\sim$ 10 kV/cm in vacuum nEDM cells (due to side walls). Can degrade due to adding (gas) comagnetometer → 70 kV/cm if in insulating fluid
***N* = no. detected neutrons**	• Current 10^{-27} *e*.cm experiments detect 200,000-300,000 in large 20 - 30 L sized cell. (UCN density in cell ~ 5-10 cm^{-3}). • Can't increase volumes much more; false EDM systematic ~ $(\text{cell length})^2$ • Also need to control B-field to $\lesssim$ 1 ppb over cell volume
***T* = interaction/useful time**	Restricted by UCN loss time on walls. But even if get longer, need to control B-field field drifts. A lot can happen in 100-1000s.

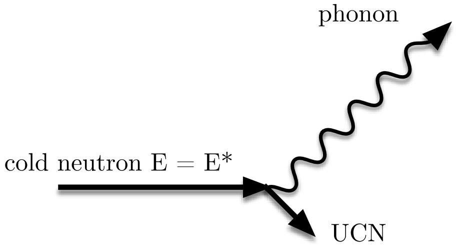
Ultracold neutrons & Superfluid ^{4}He

- **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)]



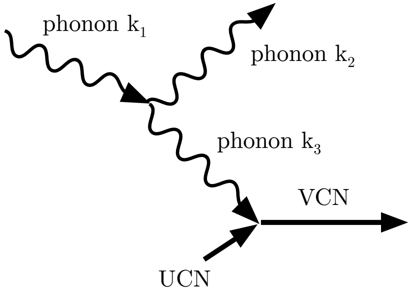
Down-scattering from single phonon
(~ T independent):



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)]



Experimental studies & demonstrations:
Golub et al, Z. Physik B (1983); Huffman et al. Nature (2000)
Zimmer et al. PRL (2011); Masuda et al. PRL (2012);
Piegsa, et al. PRC (2014); Schmidt-Wellenburg et al., PRC (2015); Leung et al. PRC (2016);

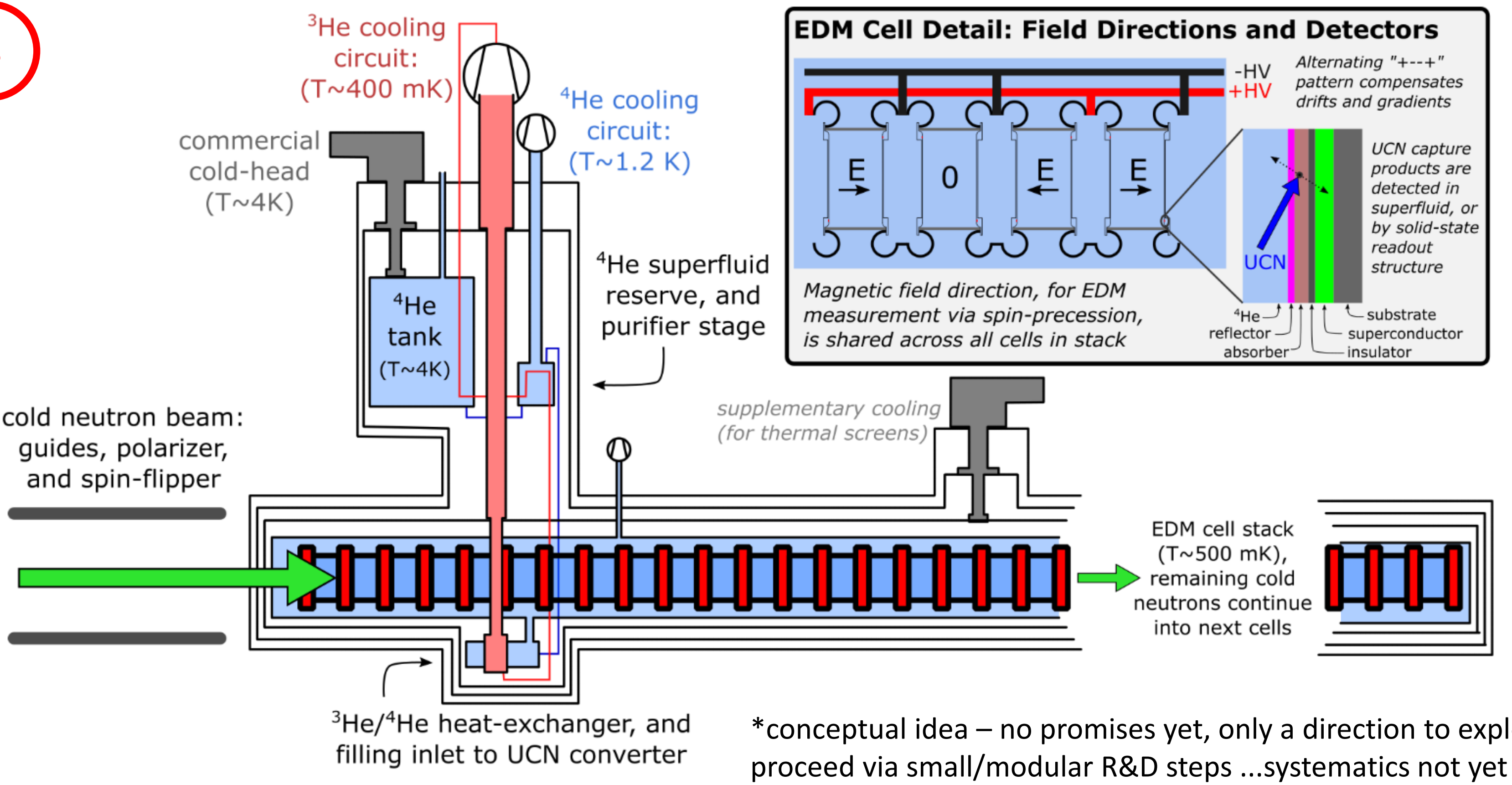
- “Super-thermal” because UCNs (~ 2 mK) not in thermal equilibrium with superfluid.
- At **T = 0.4K, up-scattering (or “thermalization loss time”) τ_{up} ≈ 20 hours**.
- Neutron absorption by ^{4}He is zero (when isotopically pure).
- **UCNs can be kept inside superfluid ^{4}He and UCNs studied *in-situ***

- 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

Skyler Degenkolb's idea:

The next generation*… scaling up!

③



^{3}He cooling circuit: (T~400 mK)

^{4}He cooling circuit: (T~1.2 K)

commercial cold-head (T~4K)

^{4}He tank (T~4K)

^{4}He superfluid reserve, and purifier stage

cold neutron beam: guides, polarizer, and spin-flipper

supplementary cooling (for thermal screens)

EDM cell stack (T~500 mK), remaining cold neutrons continue into next cells

^{3}He/^{4}He heat-exchanger, and filling inlet to UCN converter

EDM Cell Detail: Field Directions and Detectors

-HV

+HV

Alternating "+--+" pattern compensates drifts and gradients

E 0 E E

UCN capture products are detected in superfluid, or by solid-state readout structure

UCN

Magnetic field direction, for EDM measurement via spin-precession, is shared across all cells in stack

^{4}He reflector

absorber

substrate

superconductor

insulator

*conceptual idea – no promises yet, only a direction to explore! proceed via small/modular R&D steps ...systematics not yet clear

Skyler Degenkolb's idea:

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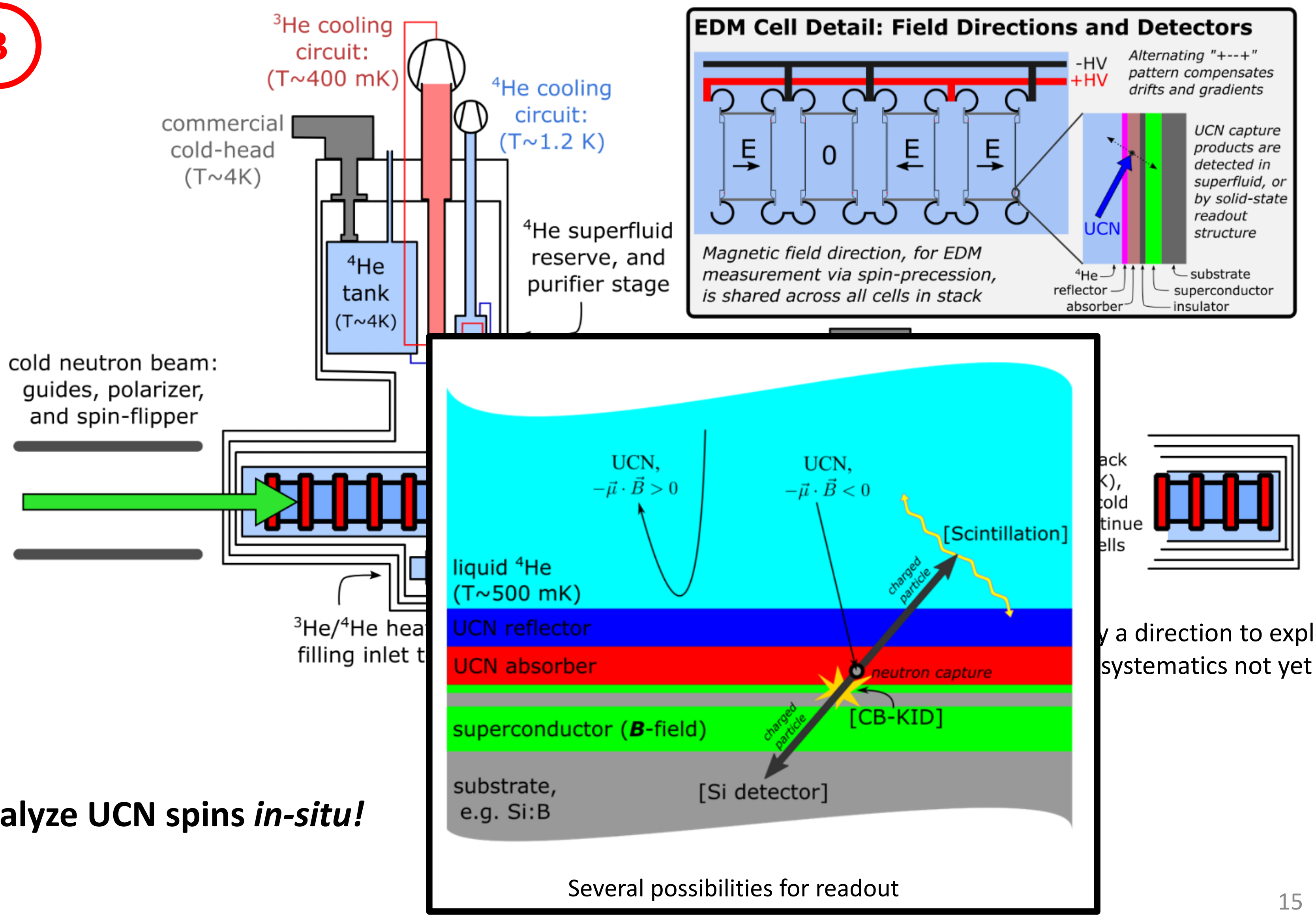
③



Several possibilities for readout

y a direction to explore!
systematics not yet clear

Analyze UCN spins *in-situ!*

NATURE | VOL 403 | 6 JANUARY 2000

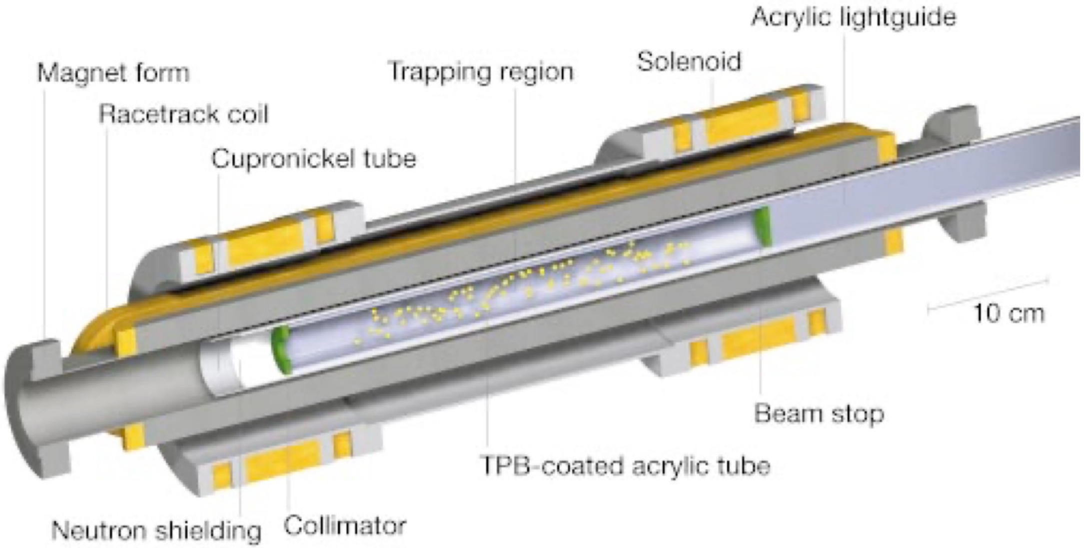
Magnetic trapping of neutrons

P. R. Huffman[*,†], C. R. Brome[*], J. S. Butterworth[*,‡], K. J. Coakley[§], M. S. Dewey[†], S. N. Dzhosyuk[*], R. Golub[‖], G. L. Greene[¶], K. Habicht[‖], S. K. Lamoreaux[¶], C. E. H. Mattoni[*], D. N. McKinsey[*], F. E. Wietfeldt[*,†] & J. M. Doyle[*]

\+ TRIUMF TUCAN UCN source

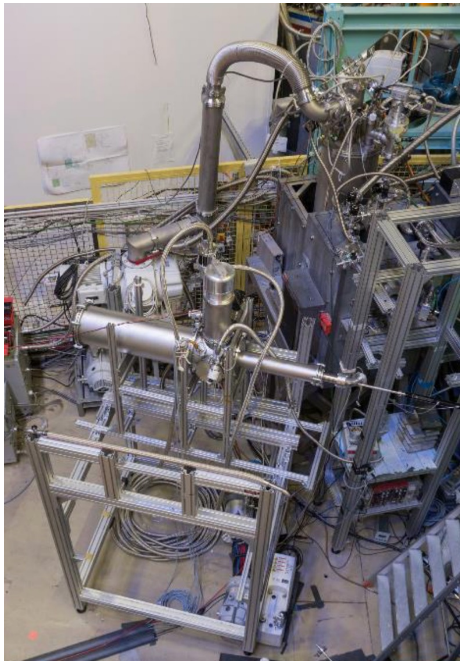
\+ Institut Laue-Langevin’s SUN-1, SUN-2, SuperSUN UCN sources

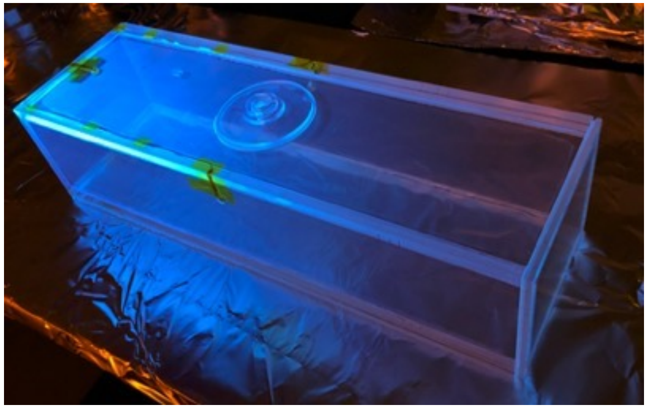
UCNs produced by cold neutron beam in Superfluid ^{4}He and then watch decay via scintillation light (n → p + e + ν + 800 keV).
With magnetic trap: no wall losses, but still β-decay τ_β = 880 s and a bit more.
They observed $\tau_{\text{loss total}} \sim$ 800 s .



Full-sized cryogenic cells demonstrated

- Full-sized 3-L measurement cell (illuminated by 300 nm UV lamp)
- Deuterated polystyrene + deuterated tetraphenyl butadiene blend (170 neV) coating on acrylic.(Material known to be high-voltage friendly)
- **Measured** $\tau_{\beta\text{+cell}}$ of 570 ± 20 s at 30 K (Single exponential decay only observed)





- Neulinger et al. (panEDM): Fluoropolymer CYTOP (115 neV) coated 3-L volume cell observed $\tau_{\beta\text{+cell}}$ = 560 s (at 10 K)

- Long $\tau_{\beta\text{+cell}}$ allows large number of UCNs accumulated per fill for in-situ production. **Polarized UCN density ~180 UCN/cm³** => ~ 500,000 UCNs per cell.
- **UCN "usefulness" time restricted by** $\boldsymbol{\tau_{\beta\text{+cell}}}$ (transverse spin coherence times are ~ 20,000 s)
- "Useful" UCN time of **1,000 s** use in a measurement cycle

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

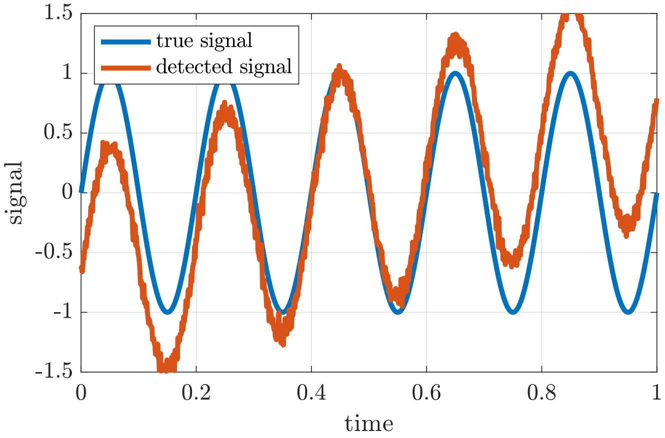
10% OFF

Atomic Clock

$26.99 ~~$30~~

Amazon.... & more

- Control and measurements of time/clocks can be done to a high precision.
  - ✓ used in Ramsey technique
- The power of a frequency measurement: need only ***relative* change** of a signal **over short time scales.** (Drifts on time scales greater than a few oscillations are suppressed)

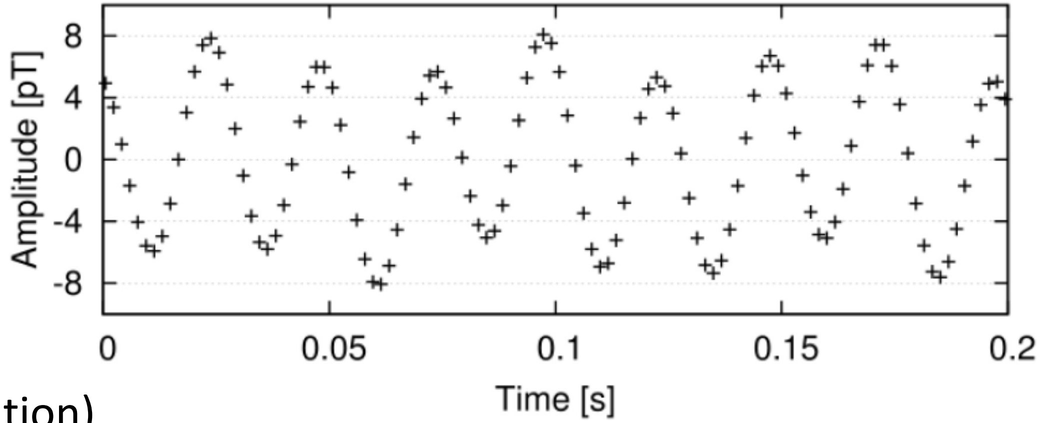


(dummy generated plots with arbitrary units to illustrate point only)

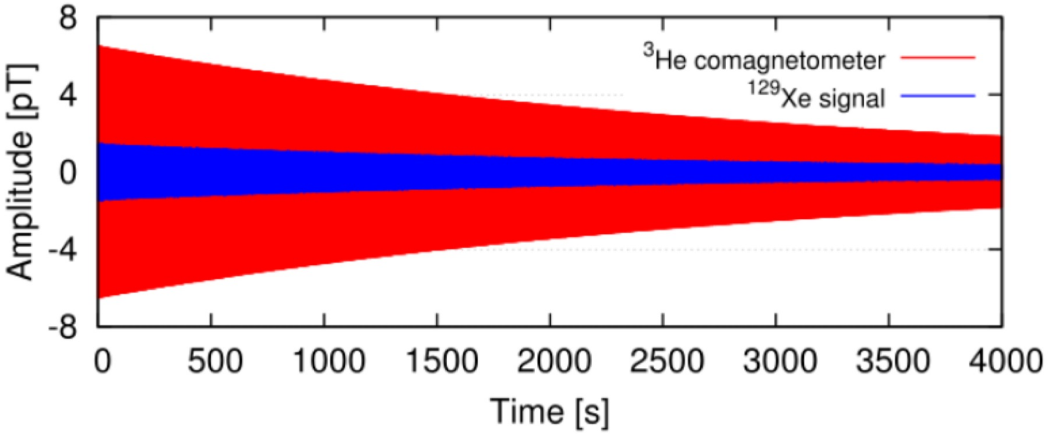
- BUT **Ramsey’s technique** only measures **final neutron phase via. counting neutrons. Disadvantages:**
  - **Blind** to frequency fluctuations
  - Need two (possibly four) repeated Ramsey cycles (with different clock frequencies within the same cell) to determine a single EDM value.
  - Each cycle takes ~100-200s. **A lot can happen in this time.**
  - **Detector efficiency, magnetic field, $\pi/2$ efficiency and other polarization, UCN source intensity drifts**, etc..
  - Can be corrected but each introduces additional statistics & systematics difficult for 10^{-28} *e*.cm level

Free precession decay observation

- Regularly done in NMR, in our field done for atomic systems, for example, ^{3}He, ^{129}Xe, ^{199}Hg (but have to worry about unwanted Stark Shifts)



(From HeXe collaboration)



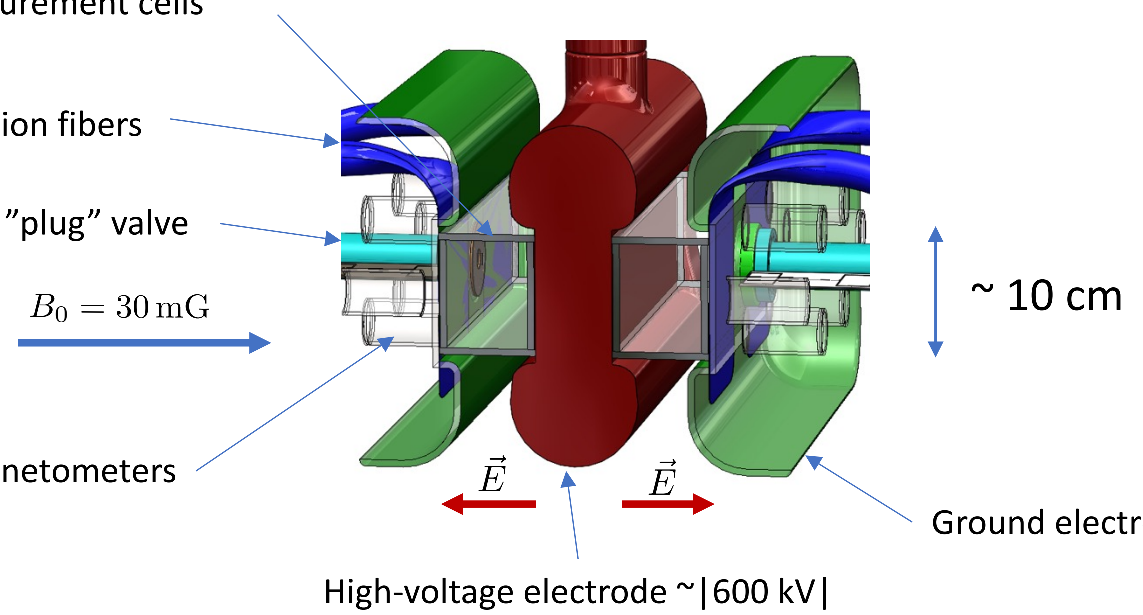
- Can it be done for neutrons?

Experimental Overview

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

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

All inside a ~ 1400 L superfluid ^{4}He bath

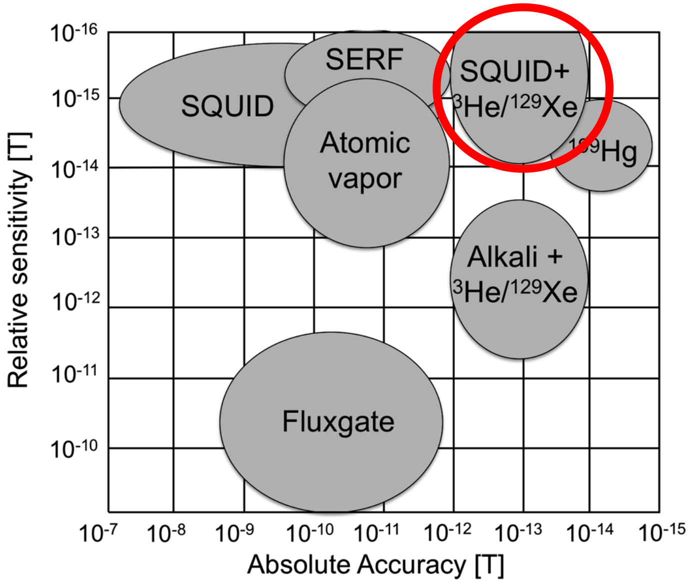


- **Double cell** setup with E-field relative to B-field opposite in each cell
- **>95% polarized ^{3}He** loaded into cell (dissolved in isotopically-pure superfluid ^{4}He at 0.4 K).
- **^{3}He serves as a comagnetometer and UCN spin analyzer** (see later)
- **In-situ super-thermal UCN (~ 100 neV) 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.

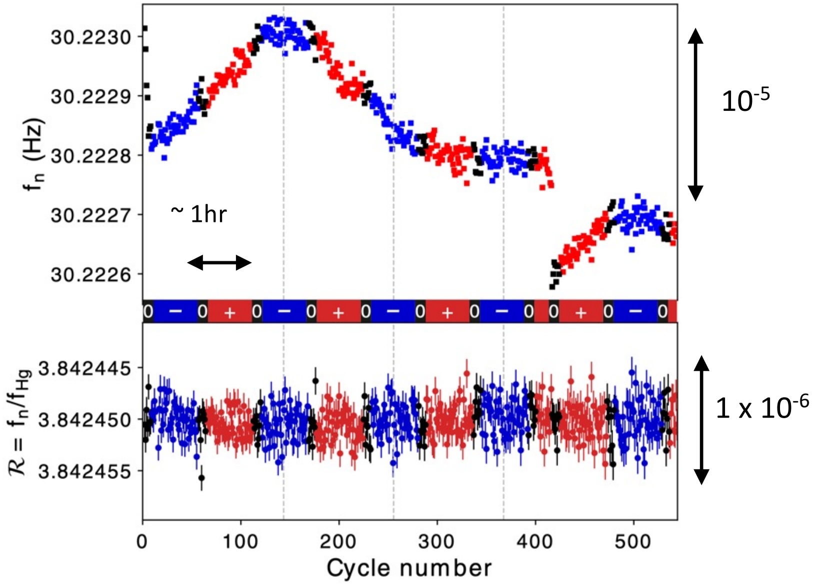
Comagnetometery

- 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)

Chupp et al. RMP (2019)



Abel et al. PRL (2020)



(for scale: 10^{-28} e.cm sensitivity -> ~ 10^{-10} fractional frequency shift)

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

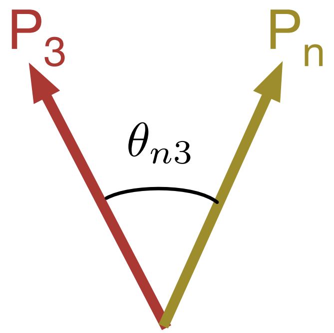
- **Capture rate** for polarized UCNs and ^{3}He in same volume :

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

number of UCNs

polarizations

angle between spins



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

^{3}He number density

or “continuous”

- Detect the 760 keV scintillation as generated ➞ **in-situ and live** 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. $\bar{\tau}_3 \approx 500\,\mathrm{s}$

- So want number density $n_3 \approx 2 \times 10^{12}$ cm^{-3} (or 10^{-10} concentration) with near $P_3 \approx 100\%$
  ➞ **Achievable with atomic beam source.**

- 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: $$d_{af} = \frac{J\hbar}{4}\left(\frac{\partial B_{0z}}{\partial z}\right)\frac{\gamma^2 \boxed{R^2}}{c^2}\left[1-\frac{\omega_0^2}{\omega_r^{\dagger 2}}\right]^{-1}$$
  Pendlebury et al. Phys. Rev. C (2004)

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

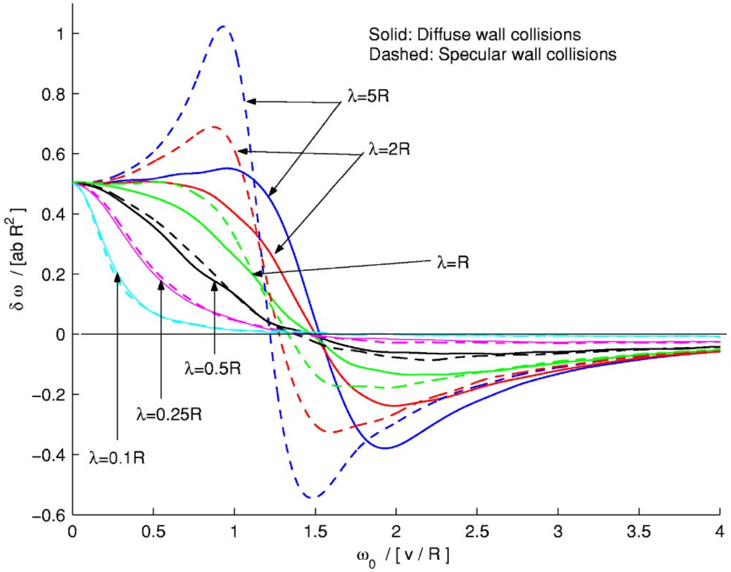
- **Note:** The transverse spin coherence time scales as R^4. Want small cells (with high UCN density)

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

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

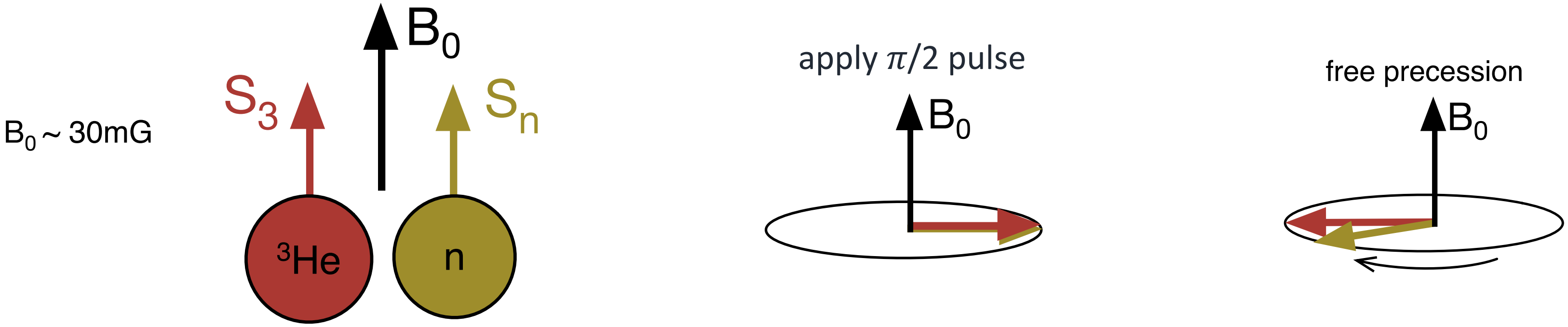
Can tune temperature to make false EDM zero by scanning T!

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 : $\gamma_3 B_0/(2\pi) \approx 100\,\mathrm{Hz}$ $\quad \gamma_3 \approx 1.1\,\gamma_\mathrm{n}$
- Scintillation light oscillation at "beat" 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 1st order drifts (e.g. + - - + - + + -) and analysis as a ”super-asymmetry"

Free precession scintillation signal

- “accepted” rate of scintillation light events:

Acceptance probability for β-decay events (~0.33)

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

Background rate (could be time-dependent)

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

no. UCNs in cell

recall: 500 s

polarizations

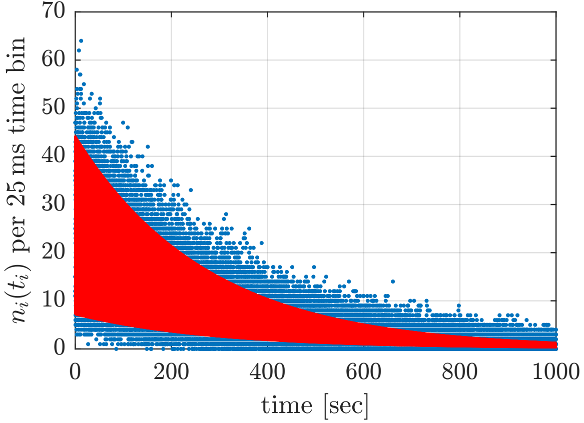
$$P_3(t)P_n(t) = P_{30}P_{n0}\exp(-t/T_{2,\mathrm{tot}}) \approx (0.98)(0.98)\exp(-t/[10,000\,\mathrm{s}])$$

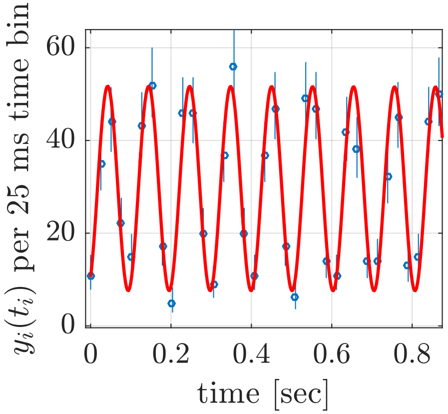
UCN spectrum

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

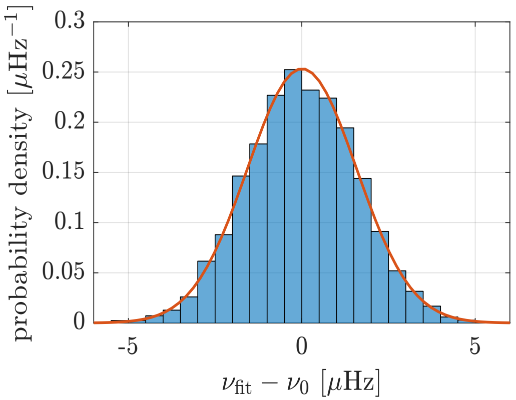
Oscillating term due to previous n-^{3}He absorption

Accepted events time-binned:





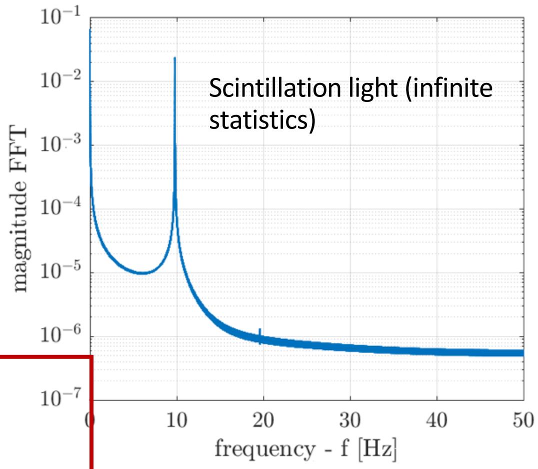
Repeat generation & fit:



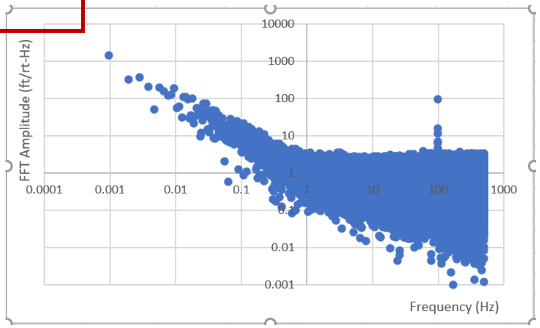
- ➢ Continuously measuring the UCN phase (relative to ^{3}He) ➞ **continuous frequency measurement** (via derivative)!
- ➢ 300 live days of running (expected to take 3 years), get **1σ nEDM error = 3 x 10^{-28} *e*.cm**

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+ 3He magnetometer 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**

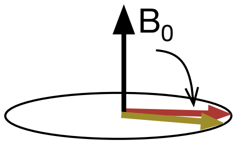


SQUID signal with noise

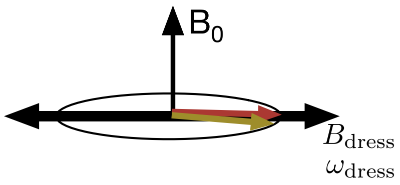


Dressed-spin mode

apply $\pi/2$ pulse



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



Cohen-Tannoudji:

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

$$\lambda = \gamma B_d / 2\sqrt{\bar{n}},$$

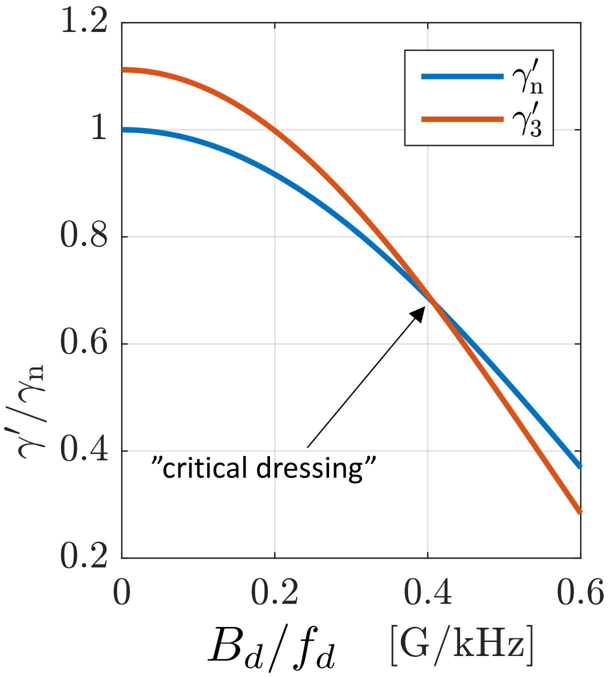
In the limit $B_{\mathrm{dress}} \gg B_0$

effective gyromagnetic ratio

0th order Bessel function

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

original



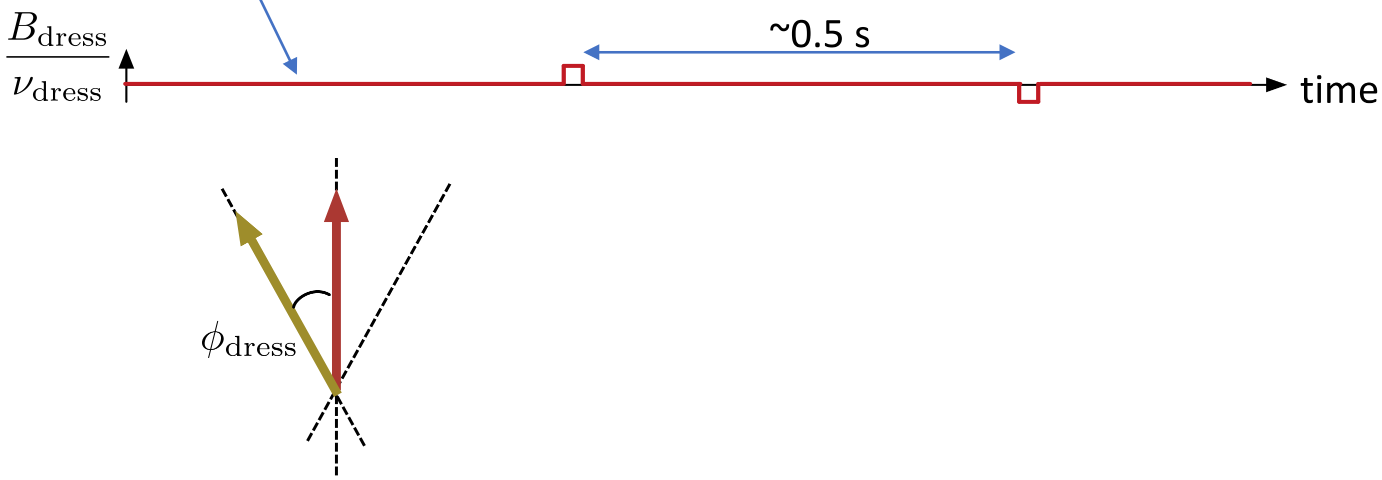
- Specific value of $B_{\mathrm{d}}/\nu_{\mathrm{d}}$ can make $\gamma'_3 = \gamma'_n$
- For instance, if $B_{\mathrm{d}} = 1\,\mathrm{G}$ is chosen, then $f_{\mathrm{d}} \approx 2.5\,\mathrm{kHz}$ is needed

- 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: $\gamma'_\mathrm{n} B_0 \pm \dfrac{2ed_n E J_0(\gamma_\mathrm{n} B_\mathrm{dress}/\omega_\mathrm{dress})}{\hbar}$
- Example of modulation with **"square wave pulses".** (Other modes possible.)

Critical dressing field to sit at a fixed ϕ_dress



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

Critical modulated dressed-spin mode

- The effect of **neutron EDM** with spin dressing: $\gamma_{\mathrm{n}}' B_0 \pm \dfrac{2ed_n E J_0(\gamma_{\mathrm{n}} B_{\mathrm{dress}}/\omega_{\mathrm{dress}})}{\hbar}$
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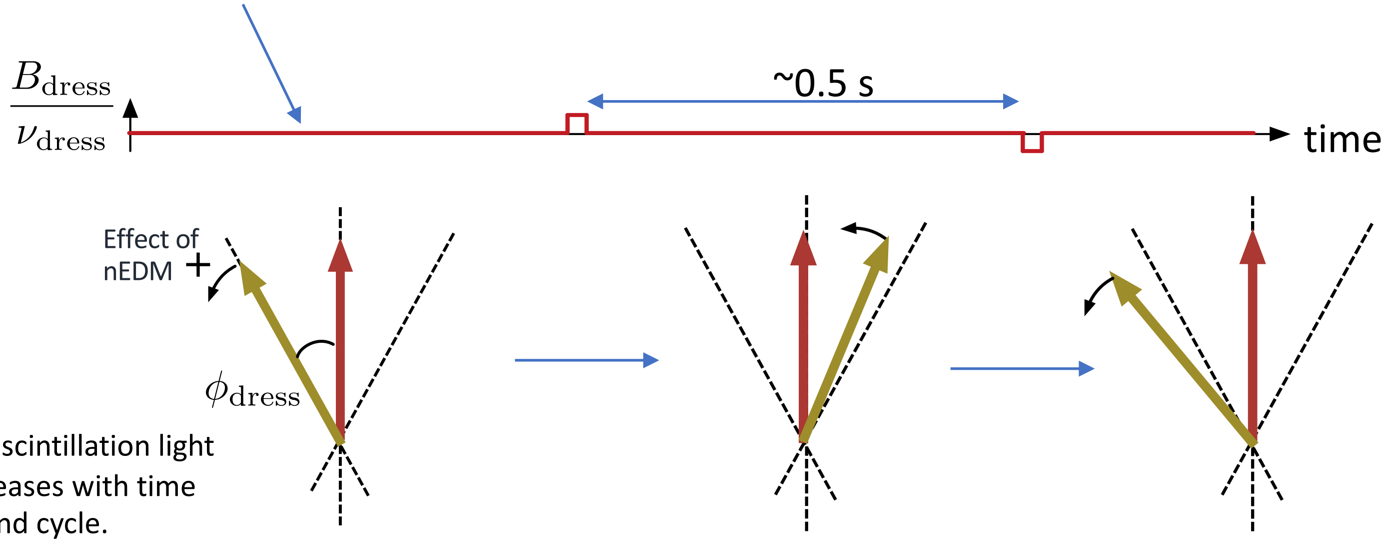
Critical dressing field to sit at a fixed ϕ_{dress}



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

If there's a nEDM scintillation light increases or decreases with time depending on E and cycle.

- Can treat each pair as **asymmetry measurement:** $A_d(t_i) = \dfrac{N_- - N_+}{N_- + N_+}$ (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.

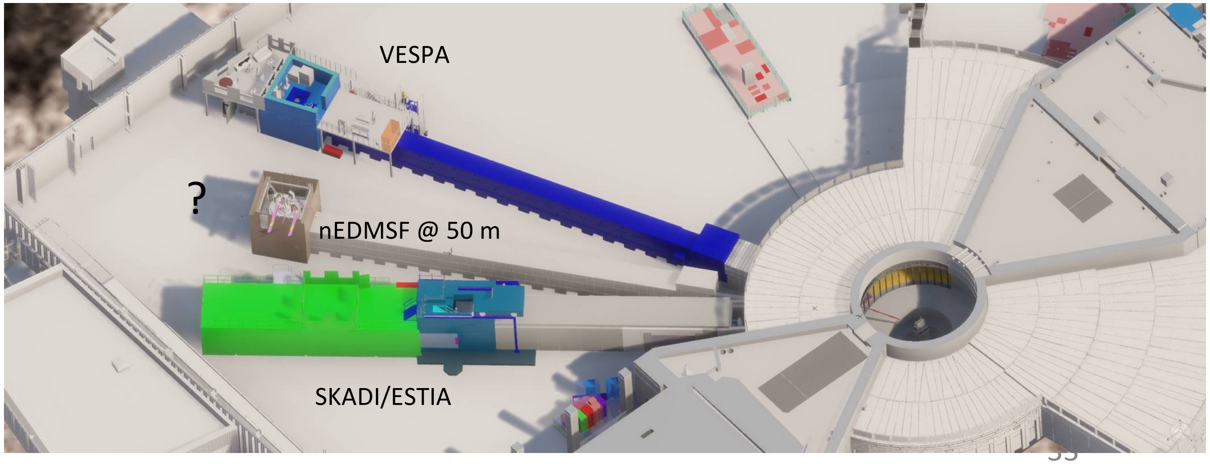
nEDM-Superfluid Status

Early tests @ ILL?
Small test apparatus

NEUTRONS
FOR SOCIETY

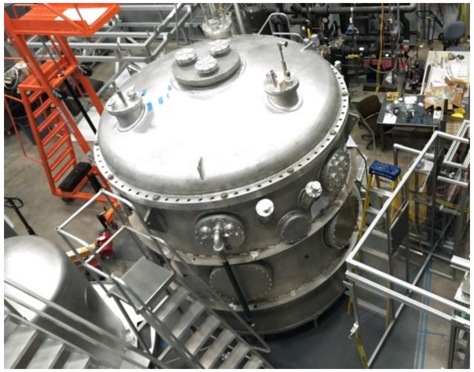
Strong support from ILL & ESS Directors.

EUROPEAN
SPALLATION
SOURCE



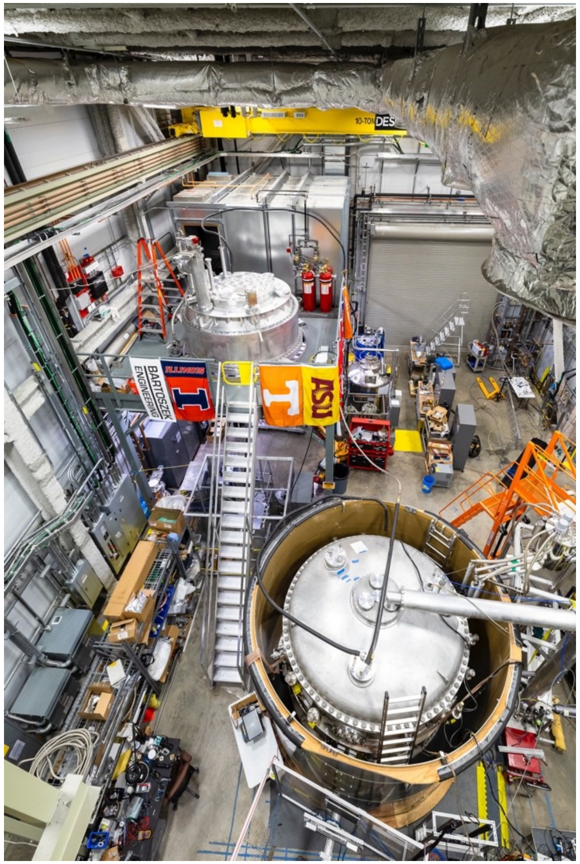
Hardware Status: Magnet System

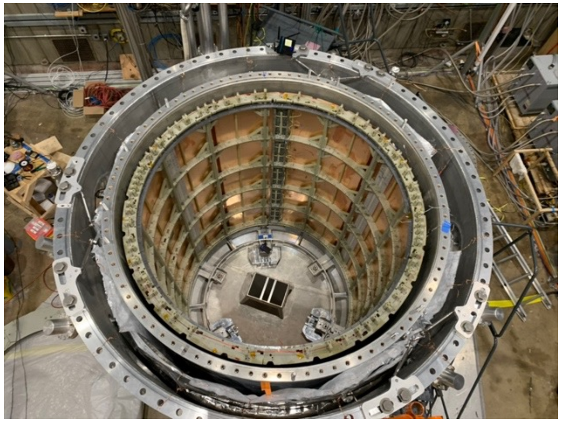
B_0 cosθ coil



Magnet system closed for cold test at ORNL

Oak Ridge National Lab





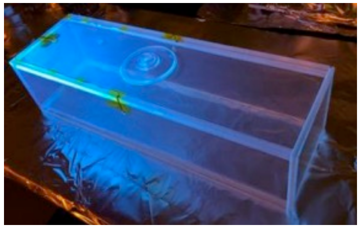
Completed B_0 coil, sc shield, vacuum chamber at ORNL

Completed magnetic shielded room at Imedco: Hägendorf, CH

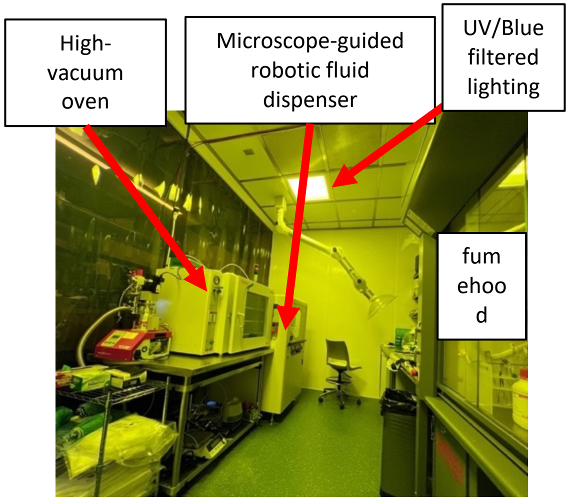
Hardware Status: Central Detector System

Completed cryostat top flange, tail for CDS testing

Half-scale HV test (T=0.4 K)

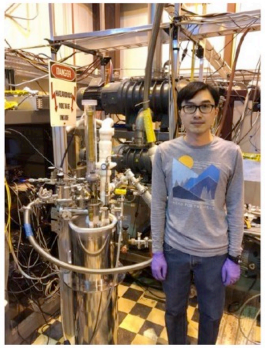


Measurement cell

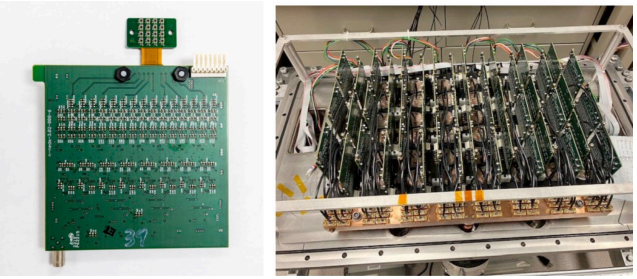


OVC composite vessel

Full-size stainless Cavallo electrodes



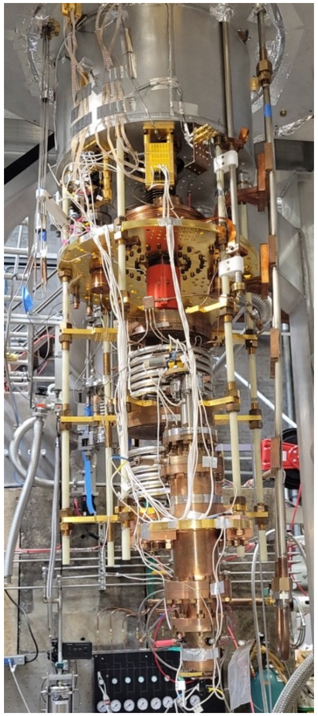
Small scale HV
N. S. Phan, et al *J. Appl. Phys.* 129, 083301 (2021)



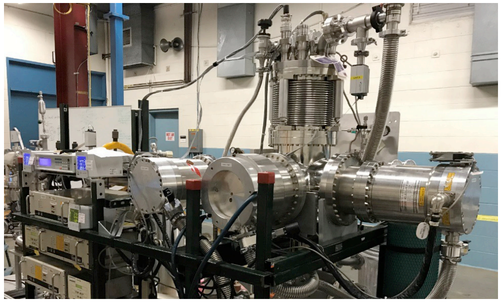
SiPM light collection

Hardware Status: Polarized ^{3}He System

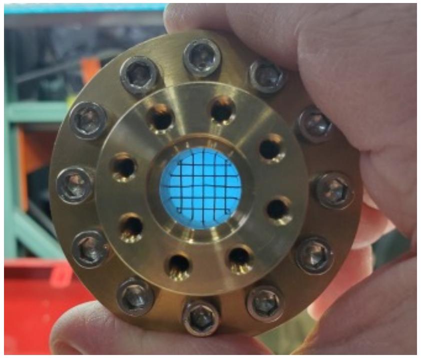
Dilution refrigerator/test cryostat



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



Atomic beam source



Nuclepore filter: magnetic particles

- To do: injection system commissioning

Summary

- The live and in-situ UCN spin analysis allows **to control drifts** in short time scales in both free precession & critical dressed-spin mode.
- Sparked some different ideas for your favorite EDM system
- For the neutron: **cryogenic UCN + ^{3}He + superfluid** scheme offers many advantages to **reach 10^{-28} e.cm (especially systematics)**
  - In-situ produced UCN in **small cell with high-density and long storage times**
  - 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**