Neutron Electric Dipole Moment (EDM) Measurements

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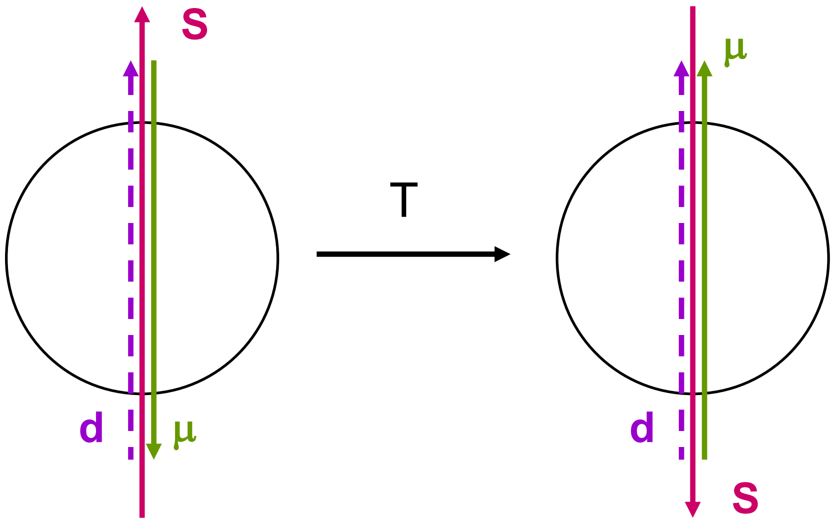
Neutron Electric Dipole Moment and T Violation

- Neutron has spin **S** (1/2)
  - has magnetic moment, **μ**
  - electric dipole moment, **d**?
    - violates time reversal symmetry



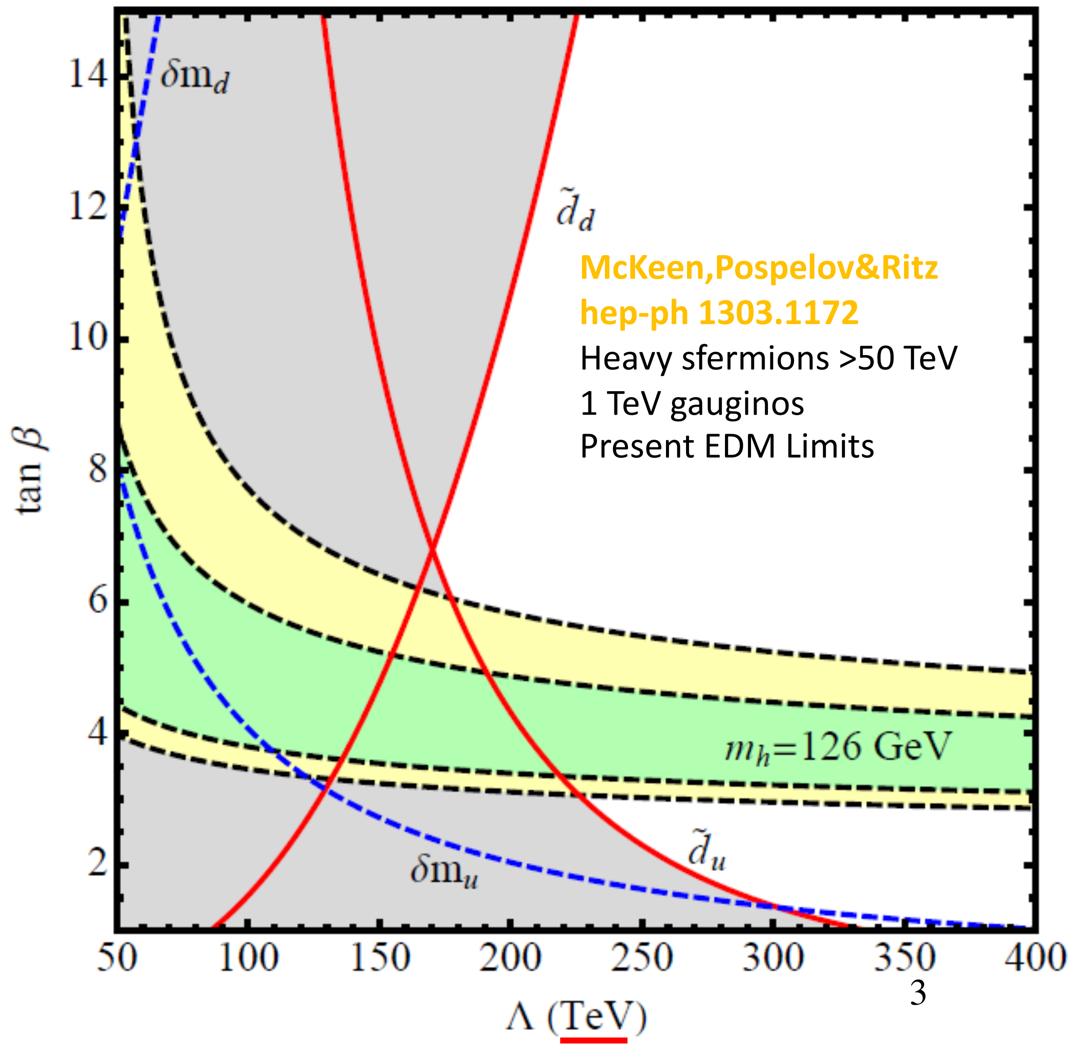
- Time reversal is violated in standard model
  - T violation observed in K^0 decays
  - Not sufficient to explain the baryon asymmetry of the Universe

- Theories beyond standard model predict CP violation
  - e.g. supersymmetry (SUSY): $\mathbf{d}_n \neq 0$

Neutron Electric Dipole Moment

Search for physics beyond the Standard Model

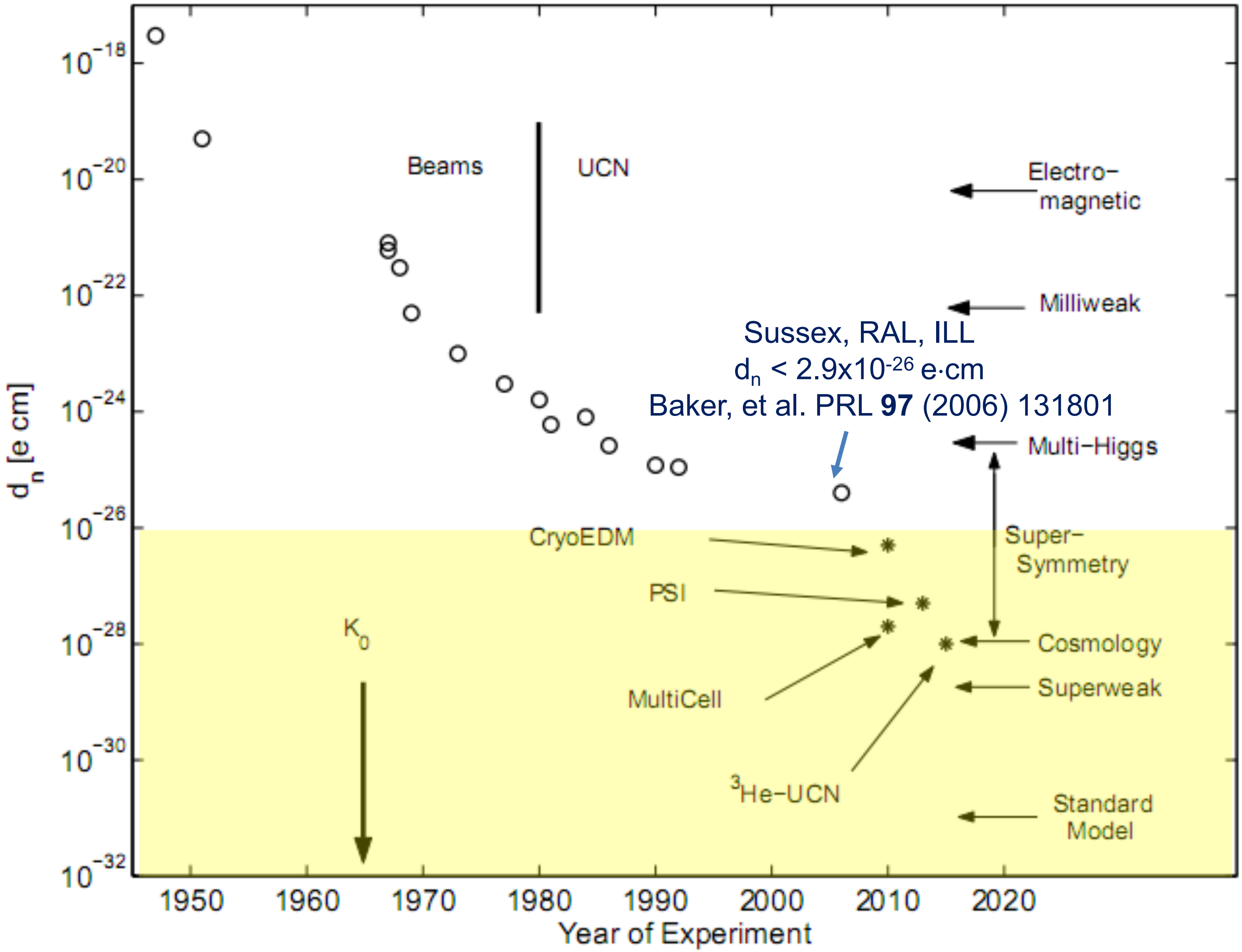
- If EDM is non-zero, must be new physics
- Strong constraints on SUSY especially with LHC data



EDM Measurements

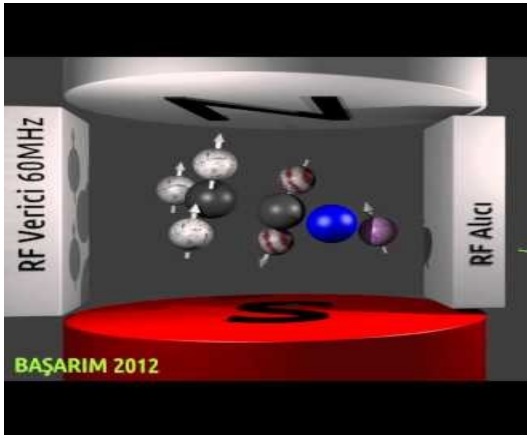
- Electron
  - paramagnetic atoms: Tl Regan, et al. PRL **88** (2002) 071805
    - $d_e < 1.6\times10^{-27}$ e·cm
  - molecules:
    - YbF $d_e < 1.05\times10^{-27}$ e·cm Hinds, et al. Nature **473** (2011)
    - ThO $d_e < 8.7\times10^{-29}$ e·cm J. Baron, et al. Science **343** (2014) 269
- Nuclei
  - Hg Griffiths, et al. PRL **102** (2009) 101610
    - $d_{Hg} < 3.1\times10^{-29}$ e·cm
  - [Ra trapped atom: ANL]
  - [p, d storage ring proposal: BNL]

Neutron EDM Measurements



nEDM Measurement

- Measure precession frequency of neutron (magnetic) moment
  - like nuclear magnetic resonance experiment



- precession frequency depends on magnetic moment, magnetic field

$$f = 2\mu_B B / h$$

- add electric field E (parallel or anti-parallel to B)

$$f = 2\left(\mu_n B \pm d_n E\right) / h$$

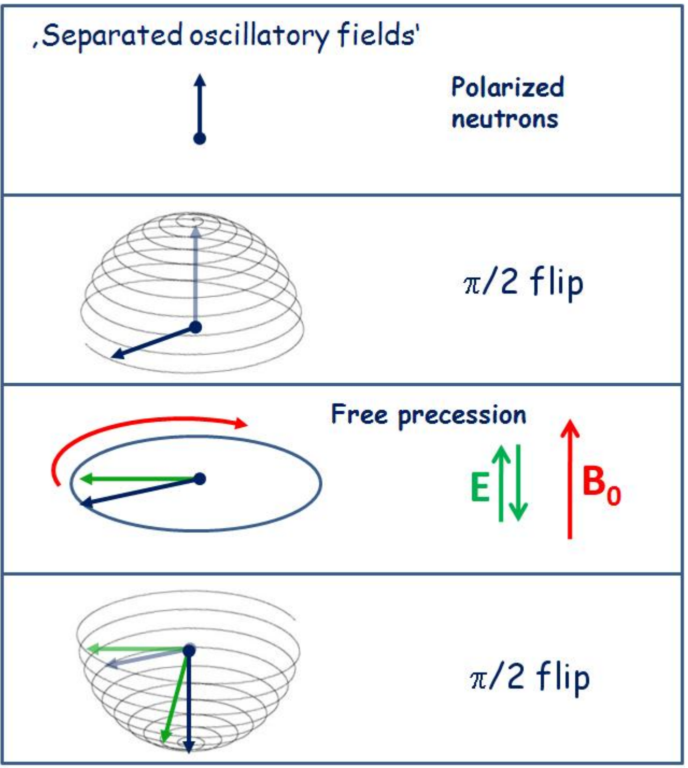
- Can isolate small $d_n E$ piece by subtracting precession frequencies

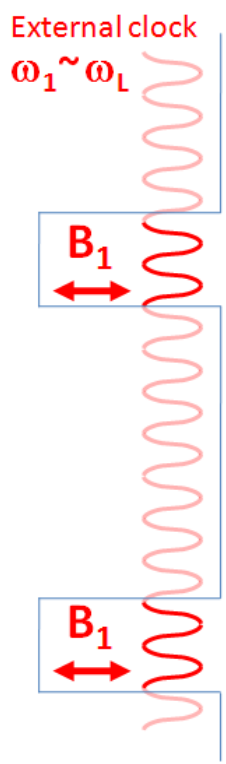
$$f_{\uparrow\uparrow} - f_{\uparrow\downarrow} = 4 d_n E / h$$

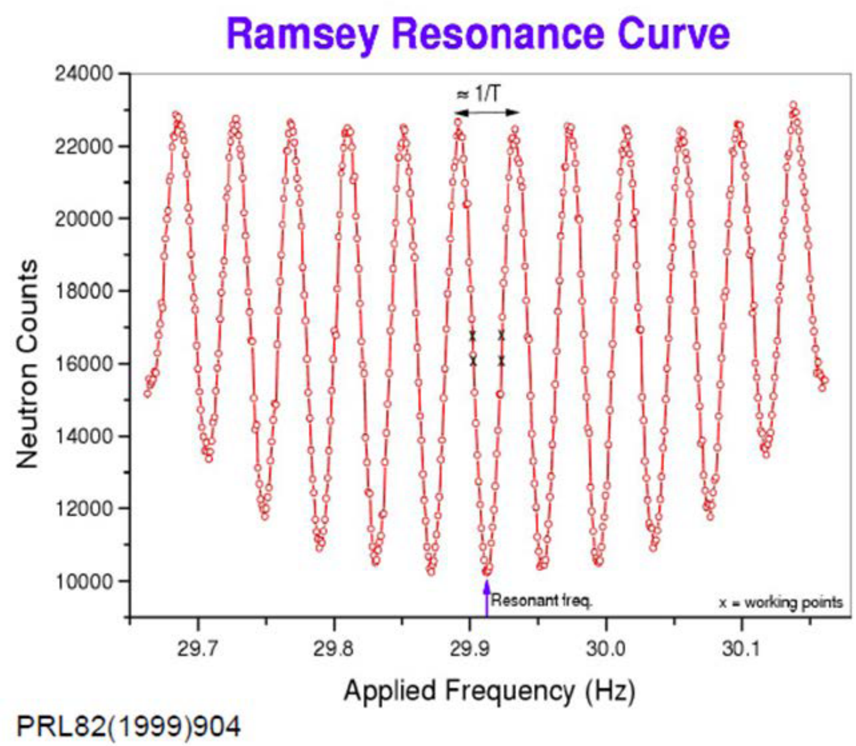
For $\mu_E = 10^{-28}\text{e}\cdot\text{cm}$ and $E = 75\text{kV/cm}$,
$\Delta f \sim 7.5$ nHz.

Separated Oscillatory Fields Methods

- Particle beam or trapped particles







Spin Analyzer

Method pioneered by
N. Ramsay

EDM changes Larmor precession:

$$\frac{h\omega_L}{2} = \mu B \pm dE$$

The First Modern Experiment

Jim Smith, ca. 1950

J. H. Smith, E. M. Purcell & N. F. Ramsey, Phys. Rev. **108** (1957) 120.

nEDM Experimental Sensitivity

- Statistical precision given by: $\sigma \propto 1/E\sqrt{Nt}$
  - E is the electric field.
  - N is the number of particles measured.
  - t is the time they are exposed to the *E* and *B* fields.

- Systematic errors, systematic errors, systematic errors…
  - Reduce and monitor magnetic field gradients
  - Multiple measurement cells with opposite $\vec{E} \cdot \vec{B}$
  - Multiple measurement techniques

Neutron EDM Searches

Experiment	UCN source	cell	Measurement techniques	σ_d Goal (10^{-28} e-cm)
				Present neutron EDM limit < 300
ILL-PNPI	ILL turbine PNPI/Solid D_2	Vac.	Ramsey technique for ω E=0 cell for magnetometer	Phase1<100 < 10
ILL Crystal	Cold n Beam	solid	Crystal Diffraction Non-Centrosymmetric crystal	< 100
PSI EDM	Solid D_2	Vac.	Ramsey for ω, external Cs & Hg comag. Xe or Hg comagnetometer	Phase1 ~ 50 Phase 2 < 5
Munich FRMII	Solid D_2	Vac.	Room Temp. , Hg Co-mag., also external 3He & Cs mag.	< 5
RCNP/TRIUMF	Superfluid ^{4}He	Vac.	Small vol., Xe co-mag. @ RCNP Then move to TRIUMF	< 50 < 5
SNS nEDM	Superfluid ^{4}He	^{4}He	Cryo-HV, ^{3}He capture for ω, ^{3}He co-mag. with SQUIDS & dressed spins, supercond.	< 5
JPARC	Solid D_2	Vac.	Under Development	< 5
JPARC	Solid D_2	Solid	Crystal Diffraction Non-Centrosymmetric crystal	< 10?
LANL	Solid D_2	Vac.	R & D, Ramsey SOF, Hg co-mag.	~ 30

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= sensitivity < 5 x 10^{-28} e-cm

Slide thanks to Brad Filippone

Some Key Technologies for Next Generation neutron EDM experiment

- Strong UCN sources with superthermal production, SO_2, SD_2, LHe, etc

- Improved control of magnetic environment: shield house, etc

- Better magnetic field measurement: co-magnetometer, SQUID, atomic vapor cell

- Improved high voltage and uniform magnetic field generation

Ultracold Neutrons

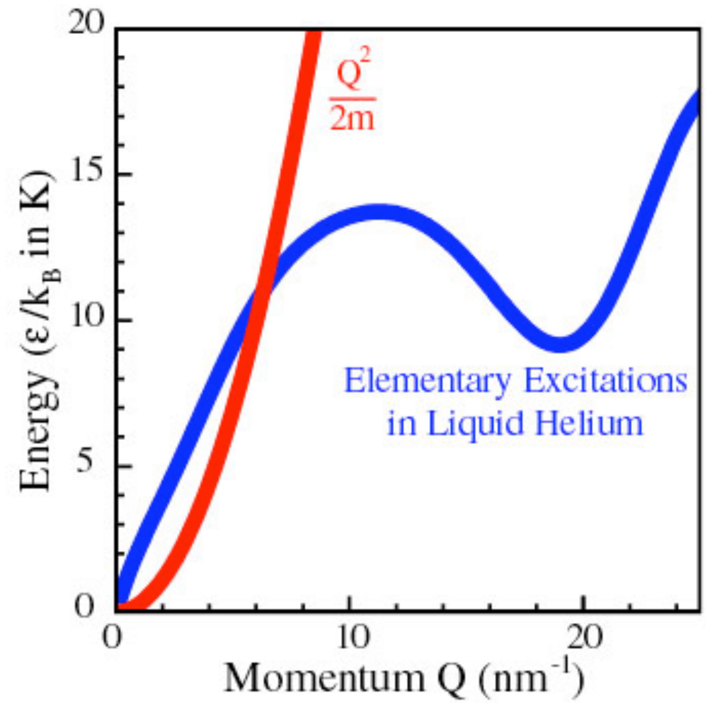
- Neutrons produced with ‘nuclear energies’ (MeV)
  - reactor, accelerator
- Slow with moderators: C, H_2O, D_2O, SD_2…
- Neutrons of sufficiently low energy interact coherently with nuclei
  - ‘ultracold neutrons’, $E \sim 100$ neV, $V \sim 5$ m/s
  - Can be trapped by materials walls

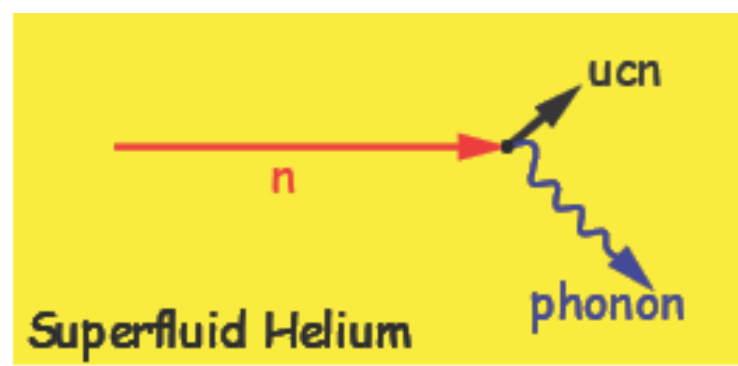
Bottle lifetime can be a few hundred seconds.

Superthermal Production of UCN

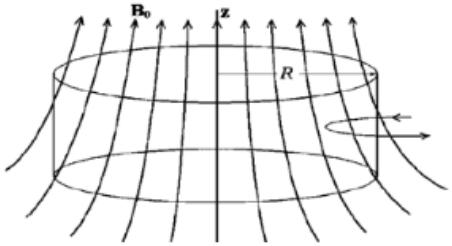
R.Golub and J.M.Pendlebury, Phys. Lett. A 62,337,(1977)

- 8.9 cold neutrons get down-scattered in superfluid ^{4}He by exciting elementary excitation.
- Up-scattering process can be suppressed at low temperature
- Solid deuterium and oxygen sources have also been studied and implemented.
- Can improve UCN density from a few UCN per cm^3 to a few hundred per cm^3, but UCN extraction is tricky.





Geometric Phase (systematics)



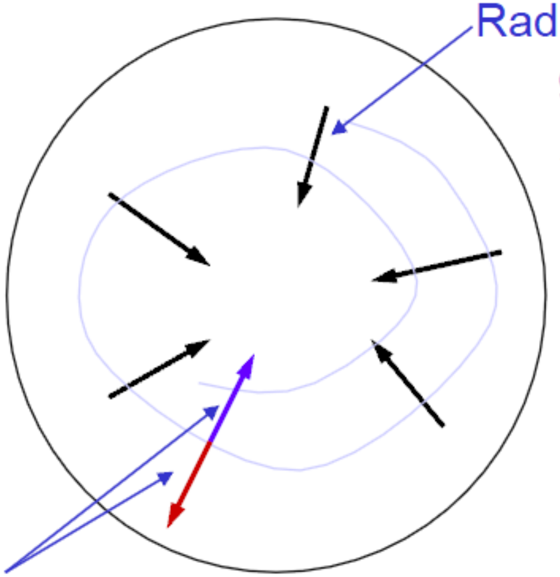
$$B_r = \frac{\partial B_0}{\partial z}\frac{r}{2} = ar$$

- Some systematics does not cancel by flipping the E field.
- Requires detailed studies

Consider particles in circular orbits with orbital frequency ω_r

Radial field from gradient

$B_r = ar$



E×v field changes sign with direction

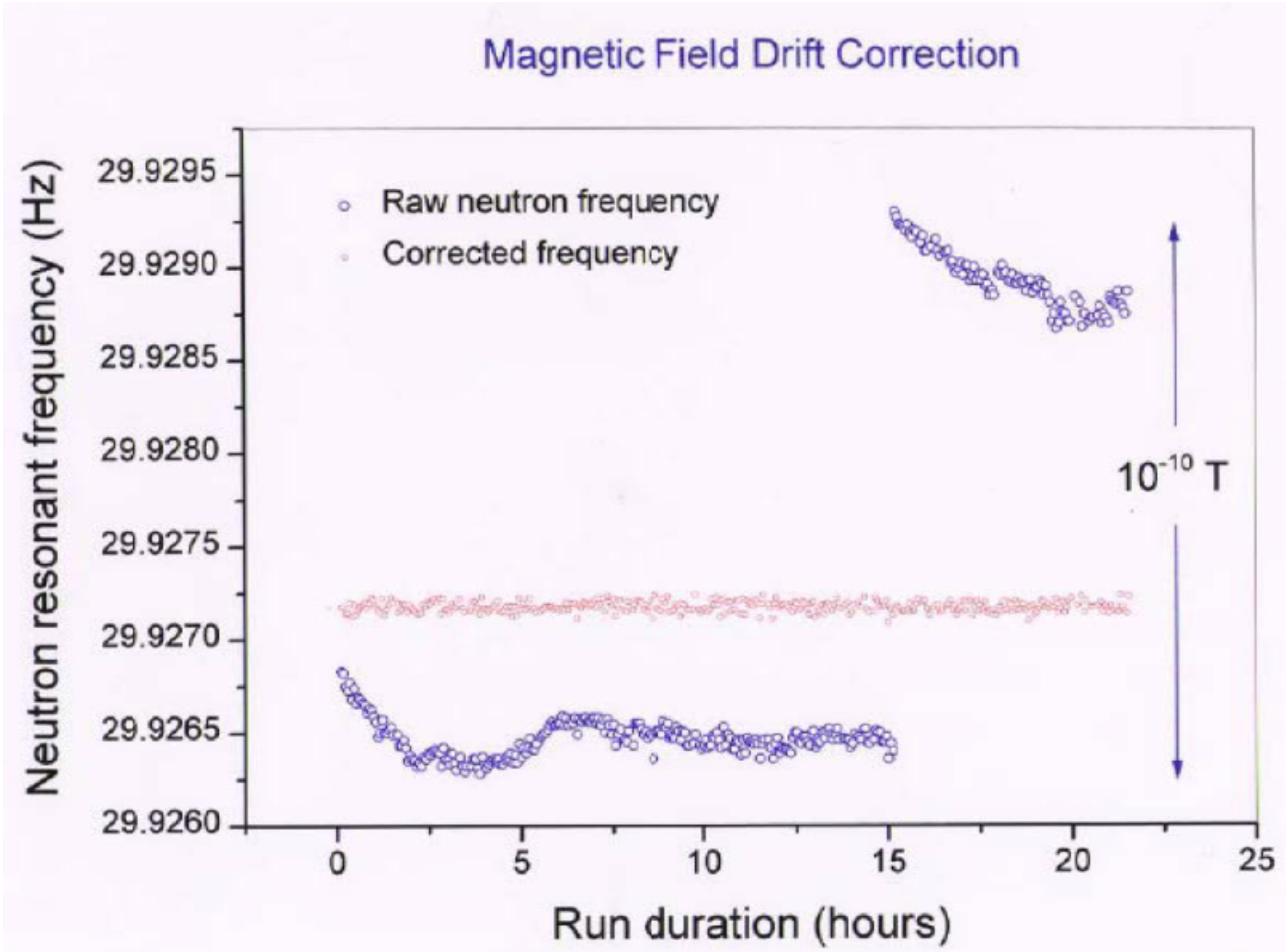
$$\delta\omega = -\frac{\gamma^2 E}{2c}\left(\frac{\partial B_{x_i}}{\partial x_i}\right)\int_{-\infty}^{\infty}\frac{\psi_i(\omega)d\omega}{(\omega_0^{\,2}-\omega^2)}$$

Where $\psi(\omega)$ is the spectral density of the velocity autocorrelation function

Effect linear in E! And B-gradients

Pendlebury et al. PRA **70**,032102 (2004)
Lamoreux and Golub, PRA **71**, 032104 (2005)

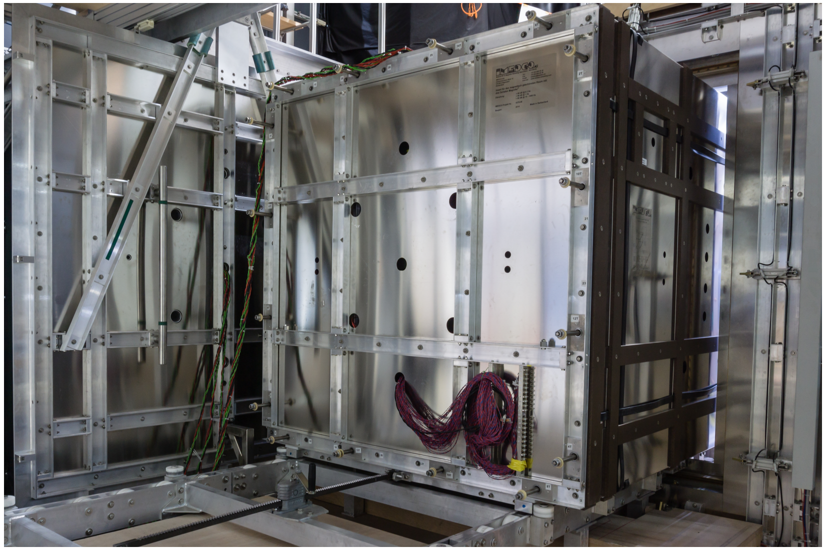
Using "Co-magnetometer" to correct for Magnetic field fluctuation

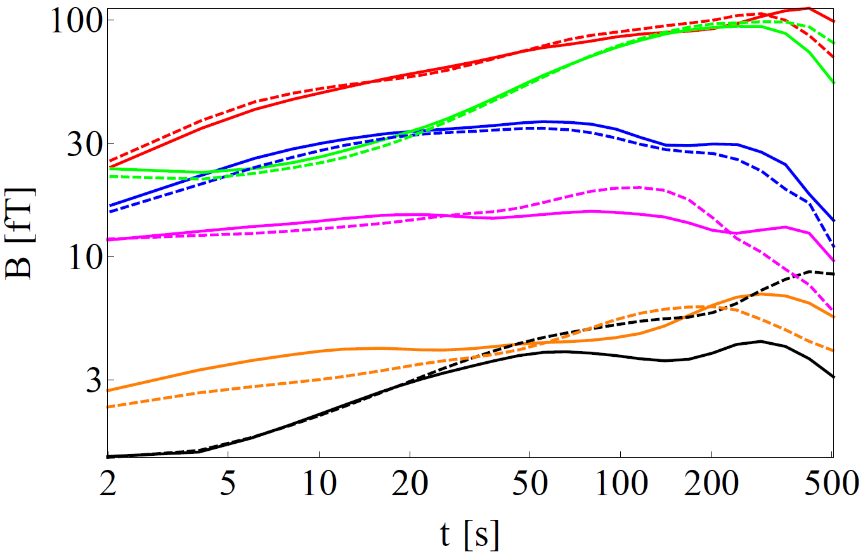


Data: ILL nEDM experiment with ^{199}Hg co-magnetometer

Magnetic Shielding House (TUM)

- Magnetic field: shielding
  - multi-layer
  - Degaussing!
  - (700 ± 200) pT and a field gradient less than 300 pT/m.
  - 10^6 damping of external field at mHz frequency.





I. Altarev, et al. Rev. Sci. Inst. **85** (2014)075106,
I. Altarev, et al. J. Appl. Phys. 117, 183903 (2015)

SNS nEDM Experiment

R. Golub and S. Lamoreaux. Physics Reports **237**, 1 (1994)

Improve statistical precision by x100.

- *Increase E*: LHe permits very large electric fields (~70 kV/cm in our measurement cell).
- *Increase N*: LHe allows production of a high density of "ultracold" neutrons (UCN). ~few 10^2 UCN/cc
- *Increase t*: With T < 0.5K UCN can be stored for ~ a thousand seconds.

Additionally liquid helium allows use of Helium-3 as a:

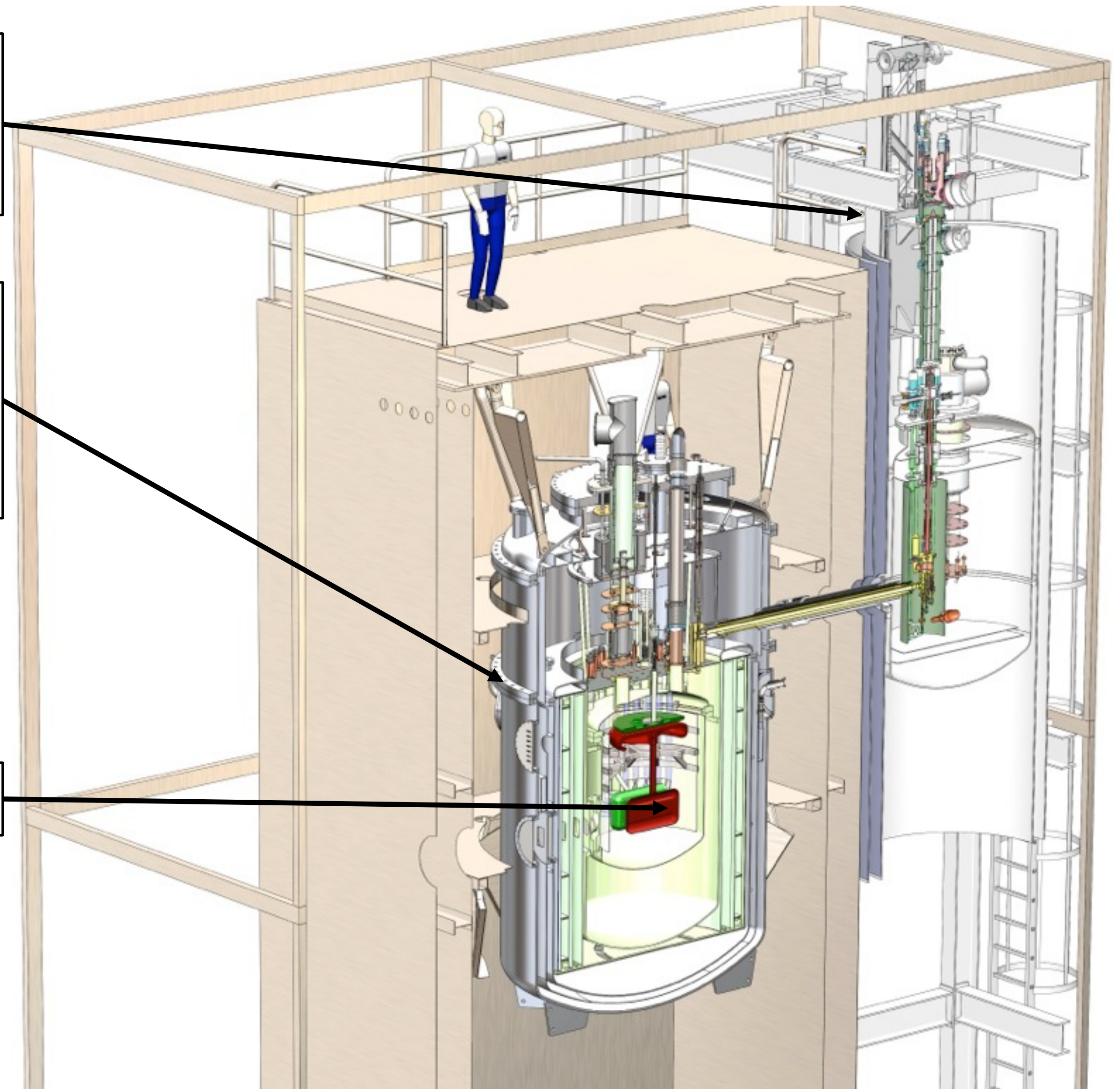
- *Spin analyzer*, providing continual measurement of the precession frequency
- *Co-magnetometer*, providing exquisite monitoring of the magnetic field

Experiment Conceptual Design

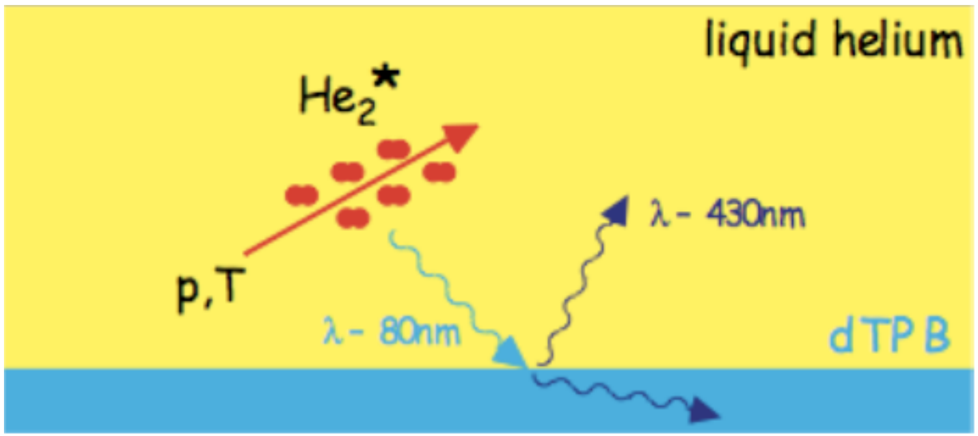
- Prepare polarized ^3He
- Isotopically purify ^4He each measurement cycle

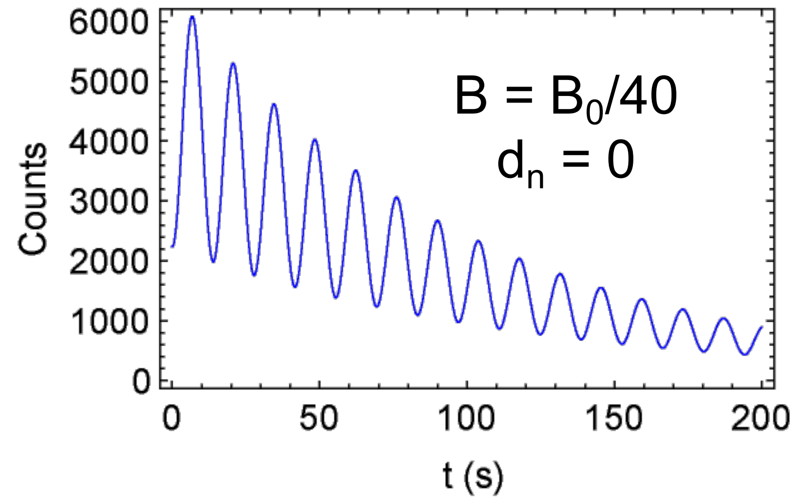
- Generate electric field
- Store ^3He, neutrons
- Monitor ^3He, neutron precession frequencies

- Generate uniform B-field



Measuring Neutron Precession using Helium Scintillation





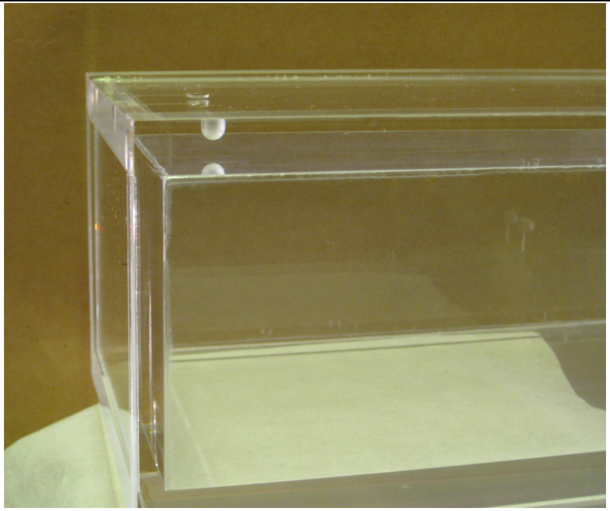
- Neutron precesses at a slight different frequency than ^3He, ~ 10%.
- Neutron absorption on ^3He is highly spin dependent. Reaction products of $n+{}^3He \rightarrow p+T$ generates UV scintillation (80 nm) in LHe.
- The UV photons are down-converted before detection.
- Spin dependent n - ^3He absorption reaction measures the difference in precession frequencies between neutron and ^3He.

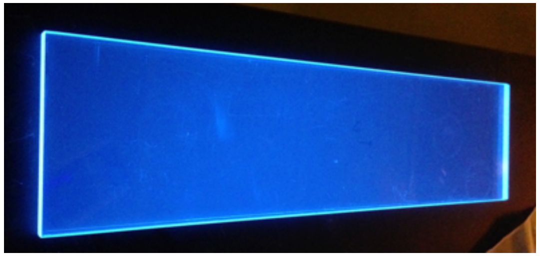
Experimental Cell and Light Collection

Cells with 1,800 second wall loss time.

Light collection test (ORNL)

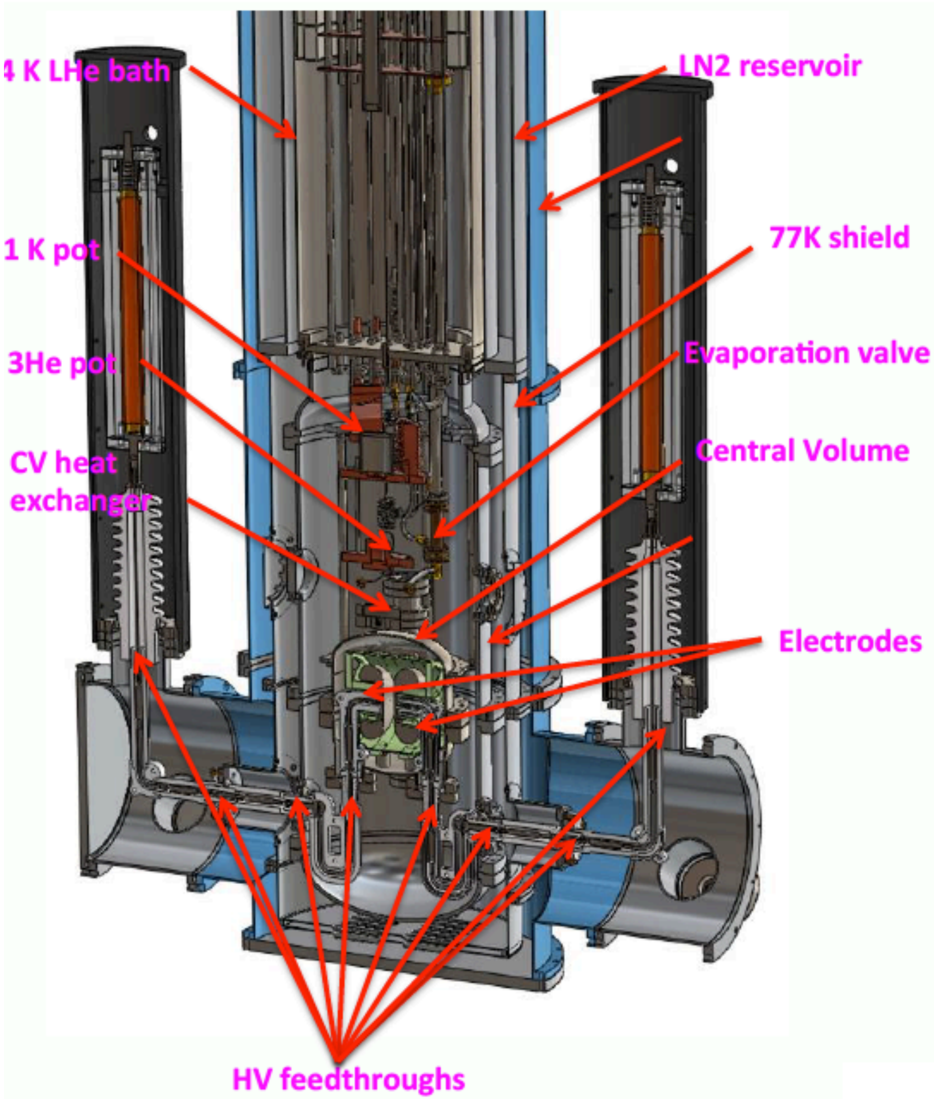
Fiber based collection scheme





Cell inner walls need to be compatible with polarized neutron and ^{3}He. dTPB in different chemical matrices under study.

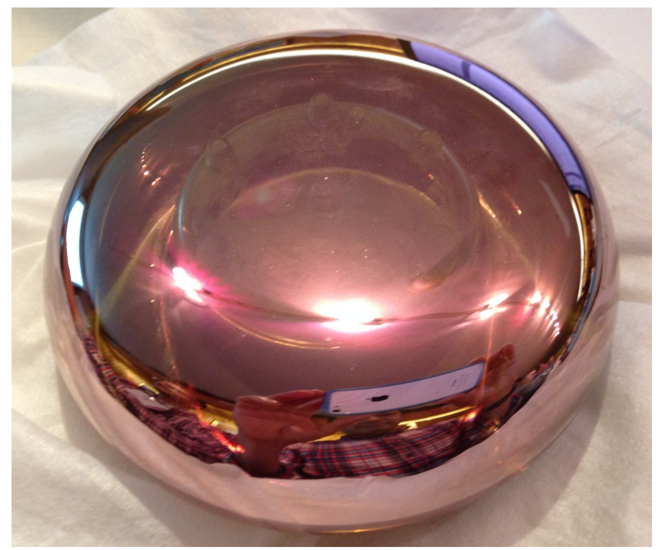
High Voltage R&D



Medium scale HV test setup at LANL

- High field in liquid helium
- High voltage generation of 500 – 600 kV
- Neutron friendly electrodes

Surface-modified acrylic electrodes achieved >85 kV/cm at 0.5K.

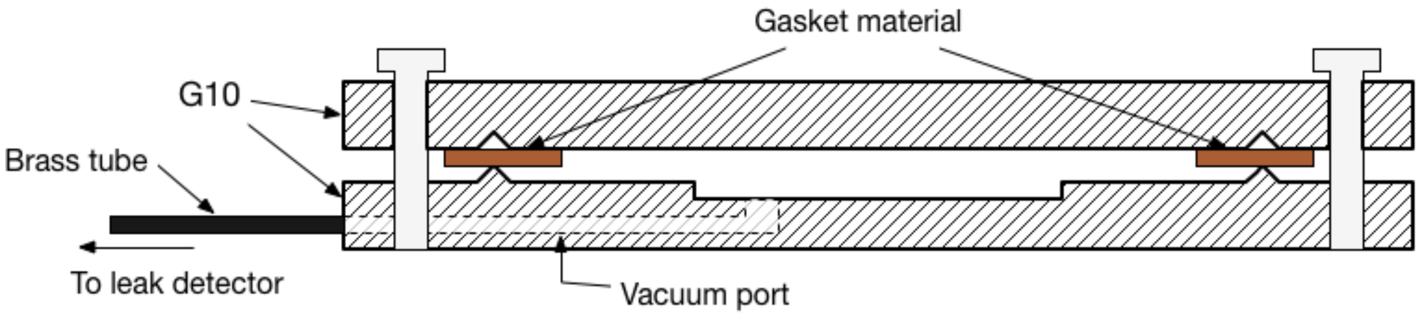


Summary

- Neutron EDM measurements are very sensitive probes for T violation and physics beyond Standard Model.
- Several experiments seek ~ x100 improvement in sensitivity
  - Systematic effects critical
  - Development and implementation of new technologies will be key.

Cryogenic Techniques Development

Superfluid-tight, non-metallic flanges demonstrated w/ 4” diameter.



Kapton bellows successfully tested for 500 strokes in liquid helium.