Neutron EDM: CP Violation in the Quark Sector

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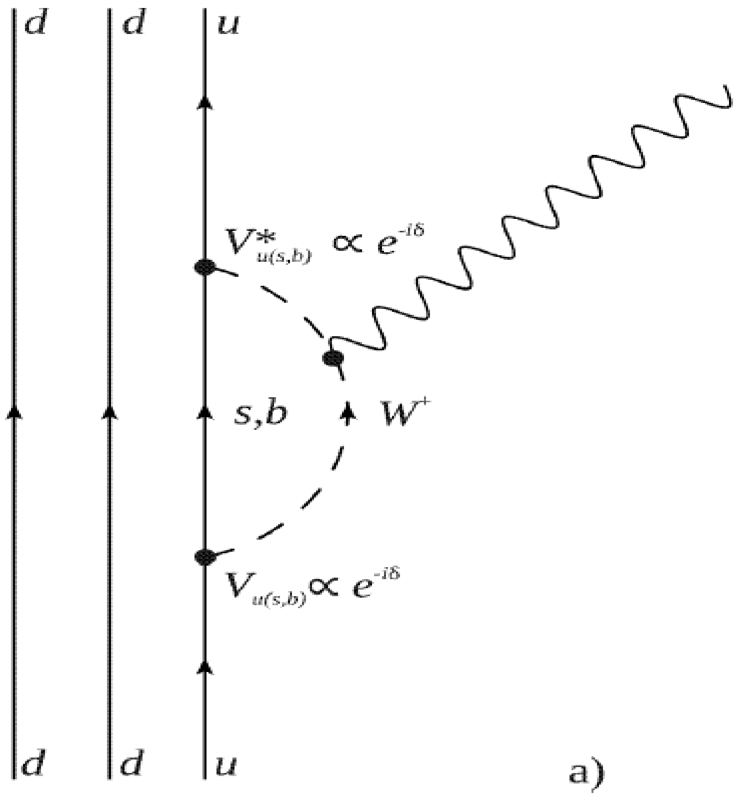
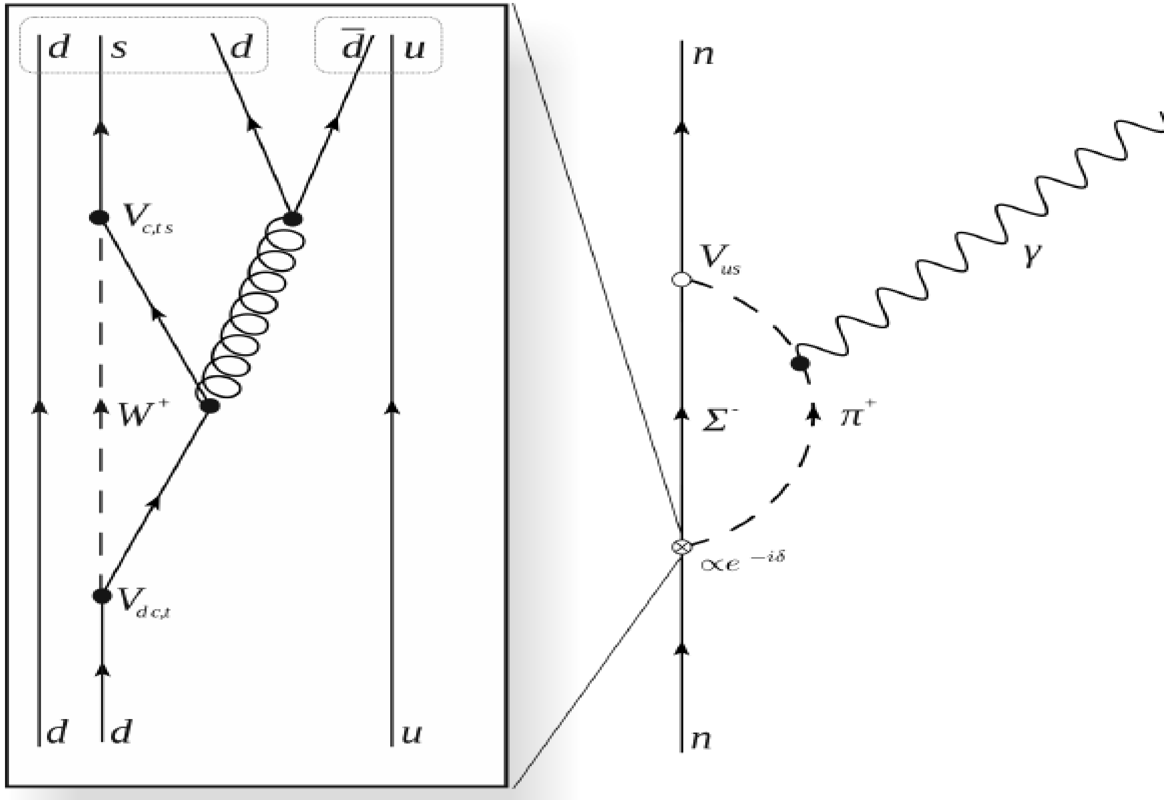
Motivation

- Neutron EDM should be ~0 by all accounts
- The presence of a non-zero nEDM is considered a sensitive probe to CP Violation
- And of course, this might help explain the matter/antimatter asymmetry (obligatory mention of BAU)
- Two sources of CP violation in the SM (given in next slide)





$$V_{\mathrm{KM}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{12}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{-i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{-i\delta} & s_{23} \\ s_{12}s_{23} - c_{13}c_{23}c_{13}e^{-i\delta} & -c_{12}s_{23}s_{13}e^{-i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$\mathcal{L}^{CP}_{QCD} = \frac{g_s^2}{32\pi^2}\,\bar{\theta}\,G^{a}_{\mu\nu}\tilde{G}^{\mu\nu,a}$$

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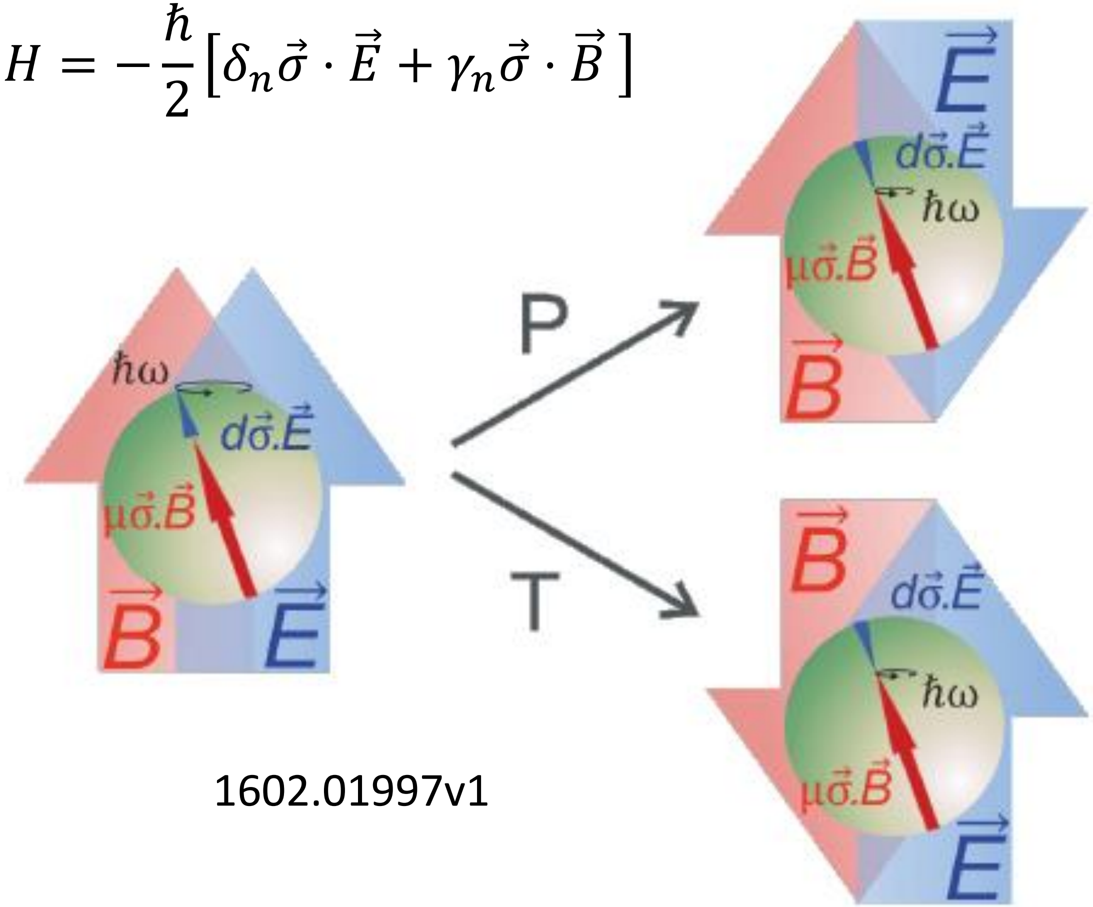
$$d_n^{CKM} \approx 1 \times 10^{-32} e \ \cdot cm$$

$$d_n^{QCD} \approx \overline{\theta} \cdot 1 \times 10^{-16} e \ \cdot cm$$

$$H = -\frac{\hbar}{2}\left[\delta_n \vec{\sigma}\cdot\vec{E} + \gamma_n \vec{\sigma}\cdot\vec{B}\,\right]$$



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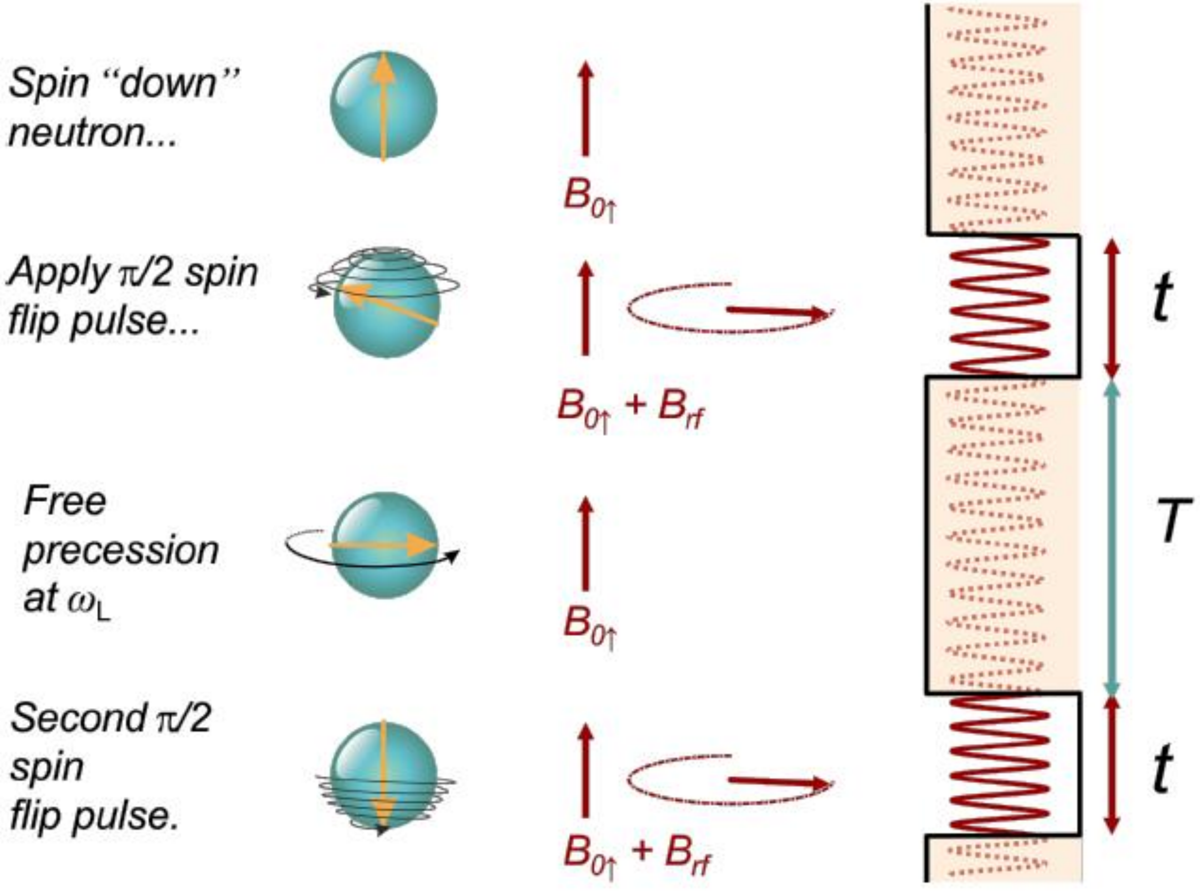
More than one way to skin a neutron

- Conversion of Ortho- to Para-Hydrogen
- Depolarization of neutron beams
- Ionization by neutrons
- Relaxation times of nuclei in liquids
- Nuclear scattering of neutrons
- Hyperfine structure studies
- Lamb-Rutheford experiment
- Interactions of electrons and neutrons (most accurate at the time)
- And of course, the ole’ one two punch: E & B (precession)

How to measure a neutron’s EDM (Ramsey)

- Measure the difference in Larmor frequencies for E parallel to B (↑↑) AND E antiparallel to B (↑↓).
- $d_n = \frac{\hbar(\omega_0^{\uparrow\uparrow} - \omega_0^{\uparrow\downarrow})}{2(E^{\uparrow\uparrow} - E^{\uparrow\downarrow})} = \frac{\hbar\Delta\omega}{4E}$
- $\sigma(d_n) = \frac{\hbar}{2\alpha TE\sqrt{\langle N\rangle}}$
- Essentially becomes a counting experiment.
- Will come back to $\mathrm{T}\sqrt{\langle N\rangle}$



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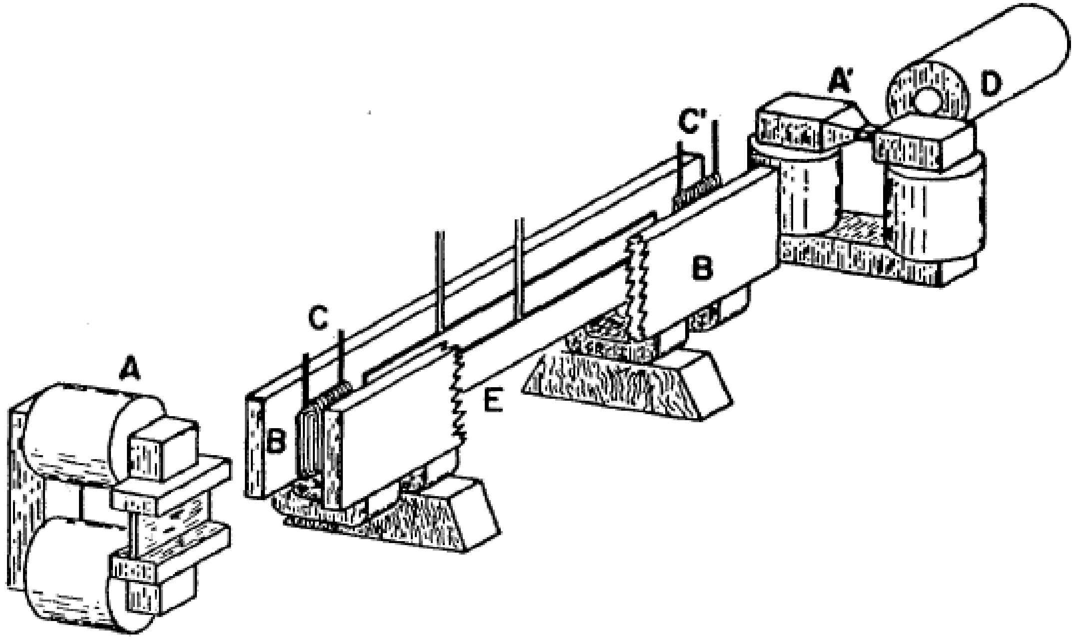
One of the first experiments

- Beam polarized at A
- Pass through homogenous B field at B.
- RF B field applied at C and C’.
- E field applied parallel to B at space between condensers E.
- Magnetized iron transmission analyzer at A’.
- BF3 Neutron Counter at D.

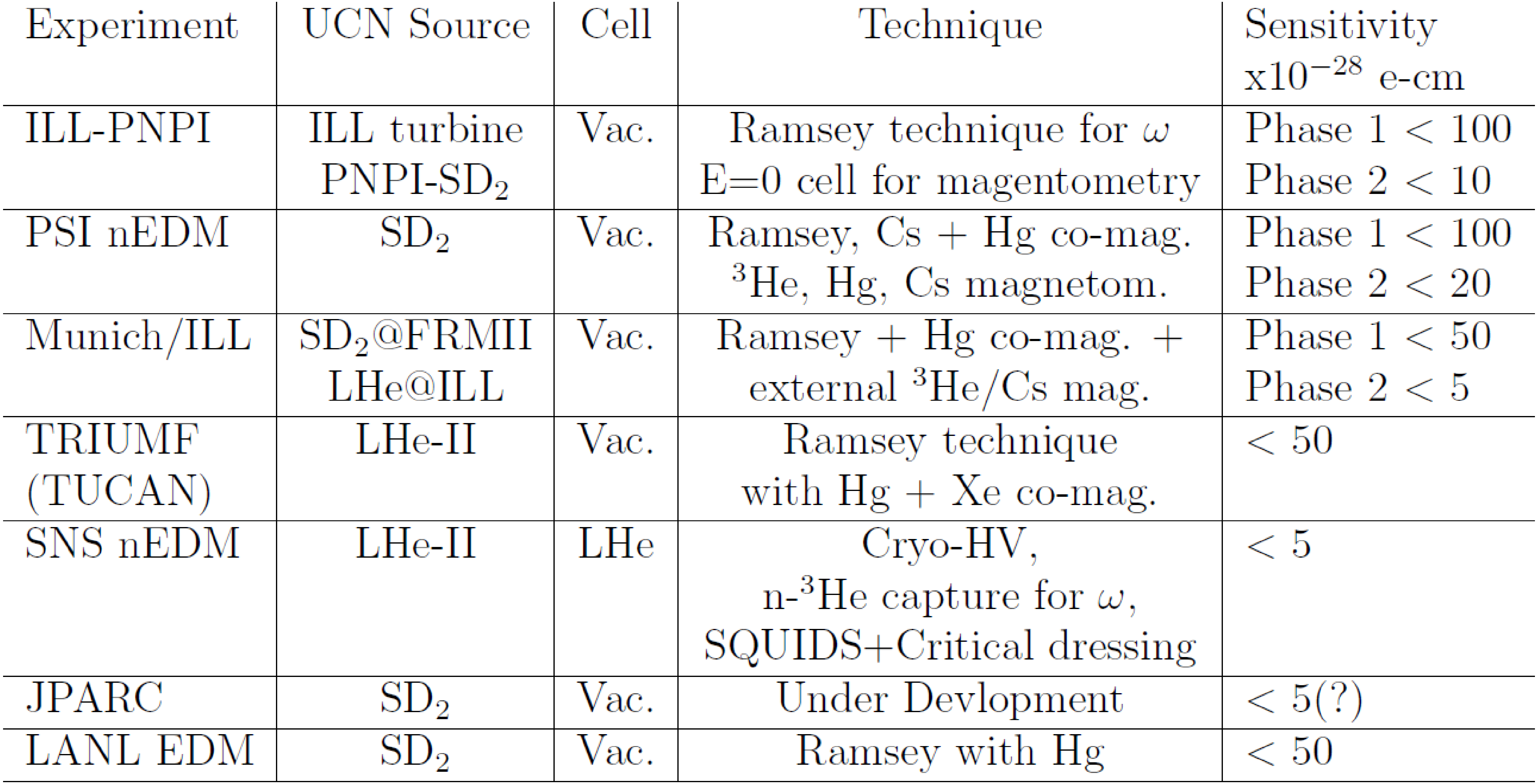


PhysRev.108.120

$$d_n < 5 \times 10^{-20} e \cdot cm$$

Ultra Cold Neutrons (UCN)

- Revisiting $\mathrm{T}\sqrt{\langle N \rangle}$ and the issue with our counting experiment.
- Neutrons with low kinetic E will reflect at material wall.
- Reflection at all angles creates a neutron container.
- Done through “super thermal” moderators (LHE-II or SD2).
- Proper control of KE in UCN important in passage and homogenous polarization of UCN sample.



Experiment	UCN Source	Cell	Technique	Sensitivity $\times 10^{-28}$ e-cm
ILL-PNPI	ILL turbine PNPI-SD_2	Vac.	Ramsey technique for ω E=0 cell for magentometry	Phase 1 < 100 Phase 2 < 10
PSI nEDM	SD_2	Vac.	Ramsey, Cs + Hg co-mag. ^{3}He, Hg, Cs magnetom.	Phase 1 < 100 Phase 2 < 20
Munich/ILL	SD_2@FRMII LHe@ILL	Vac.	Ramsey + Hg co-mag. + external ^{3}He/Cs mag.	Phase 1 < 50 Phase 2 < 5
TRIUMF (TUCAN)	LHe-II	Vac.	Ramsey technique with Hg + Xe co-mag.	< 50
SNS nEDM	LHe-II	LHe	Cryo-HV, n-^{3}He capture for ω, SQUIDS+Critical dressing	< 5
JPARC	SD_2	Vac.	Under Devlopment	< 5(?)
LANL EDM	SD_2	Vac.	Ramsey with Hg	< 50

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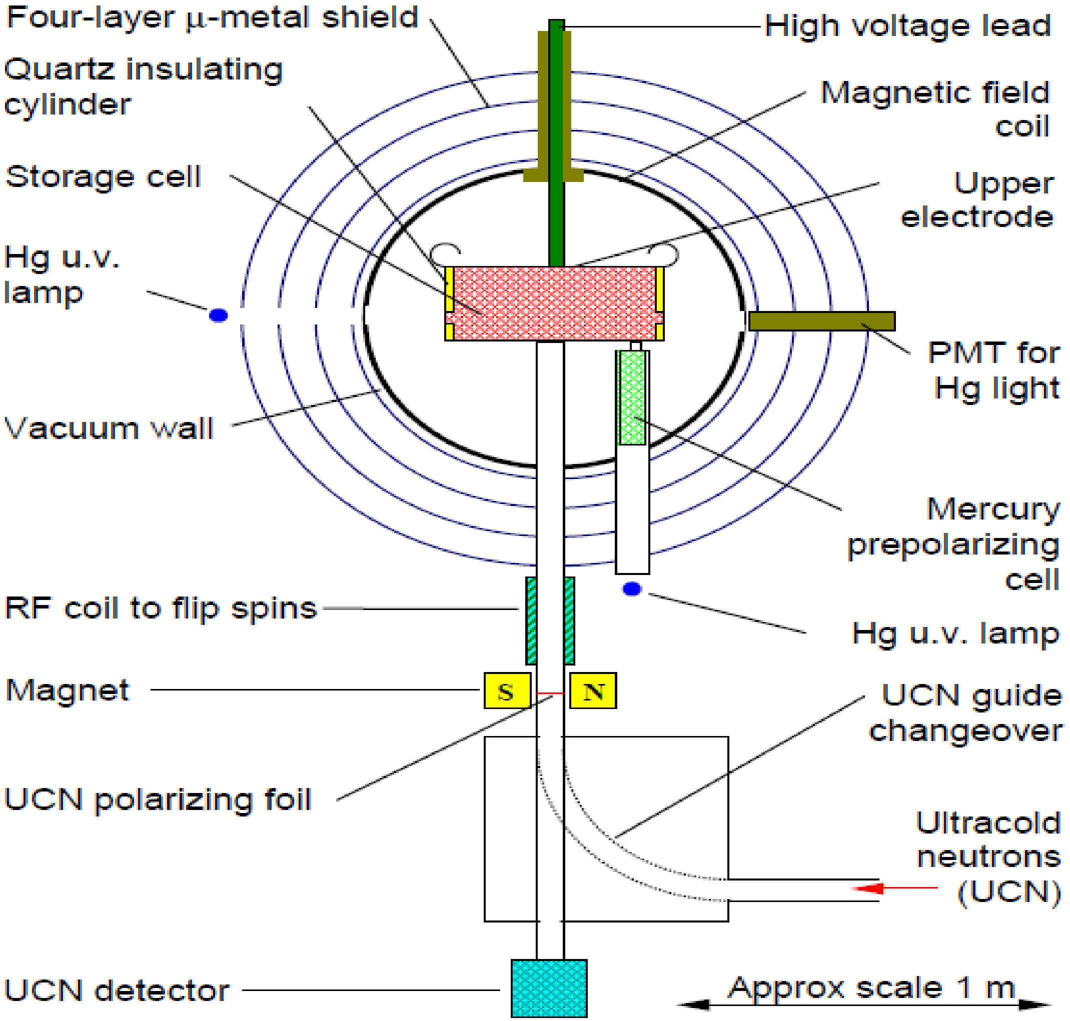
Current Best Measurement @ ILL

- UCN polarized by iron foil enter trap with uniform E and B.
- Use oscillating B fields near Larmor frequency (Ramsey)
- After osc.->free prec.->osc., neutron pol. should match init. pol.
- Dump neutrons through polarizing foil (spin analyzer)
- UCN detector measures neutrons through ^{3}He capture.
- Repeat experiment with opposite E field direction.

$$d_n < 0.3 \times 10^{-26} \mathrm{e} \cdot cm$$



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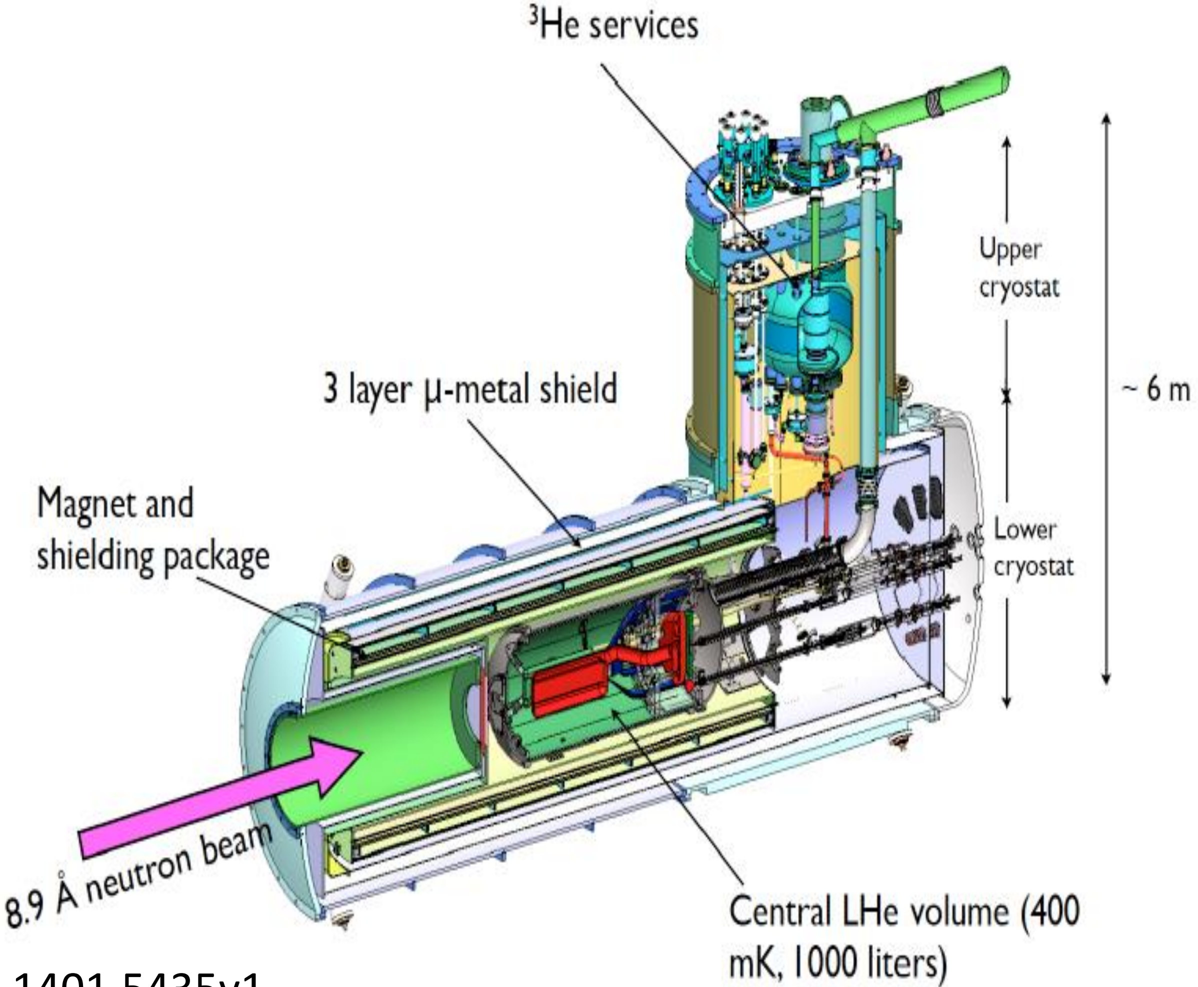
Next Generation: SNS at Oakridge NL

- Generate UCN using ^{4}He.
- Use ^{3}He as co-magnetometer and spin analyzer.
- Apply B field & large E field in LHe filled chamber.
- Neutron capture by ^{3}He is spin dependent and creates scintillation light.
- Measure difference of n & ^{3}He precession frequency (free precession or dressed spin method).



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Conclusion

- New and improved methods are being explored to measure nEDM
- Hope to gain up to two orders of magnitude in sensitivity within the next ~5 years.
- Still a long way to go:
  - Experiment: $d_n < 5 \times 10^{-28} e \cdot cm$ (optimistically)
  - SM Theory: $d_n < 1 \times 10^{-32} e \cdot cm$
- Imperative Innovations for the Future:
  - Better generation of UCN and storage
  - Higher E field applied
  - Better Magnetometers

References

- "The Quest for an Electric Dipole Moment of the Neutron" - P.Schmidt-Wellenburg [1602.01997v1] (2016)
- “Worldwide Search for the Neutron EDM” - B.W. Filippone [1810.03718v1] (2018)
- "On the Possibility of Electric Dipole Moments for Elementary Particles and Nuclei" - E.M. Purcell and N.F. Ramsey [PhysRev.78.807] (1950)
- "Experimental Limit to the Electric Dipole Moment of the Neutron" - J.H. Smith, E.M. Purcell, and N.F. Ramsay [PhysRev.108.120] (1957)
- “An Improved Experimental Limit on the Electric-Dipole Moment of the Neutron” – C.A. Baker et al. [0602020v3] (2006)

References

- “A Revised Experimental Upper Limit on the Electric Dipole Moment of the Neutron” – J.M. Pendlebury et al. [1509.04411v3] (2015)
- “High Electric Field Development for the SNS nEDM Experiment” – T.M. Ito et al. [1401.5435v1] (2014)
- “nEDM at SNS” - T. M. Ito, nEDM workshop at LANL [LA-UR-12-25394] (2012)
- Great paper covering most of the field:
- “Experimental Searches for the Neutron Electric Dipole Moment” - S K Lamoreaux and R Golub 2009 *J. Phys. G: Nucl. Part. Phys.* **36** 104002

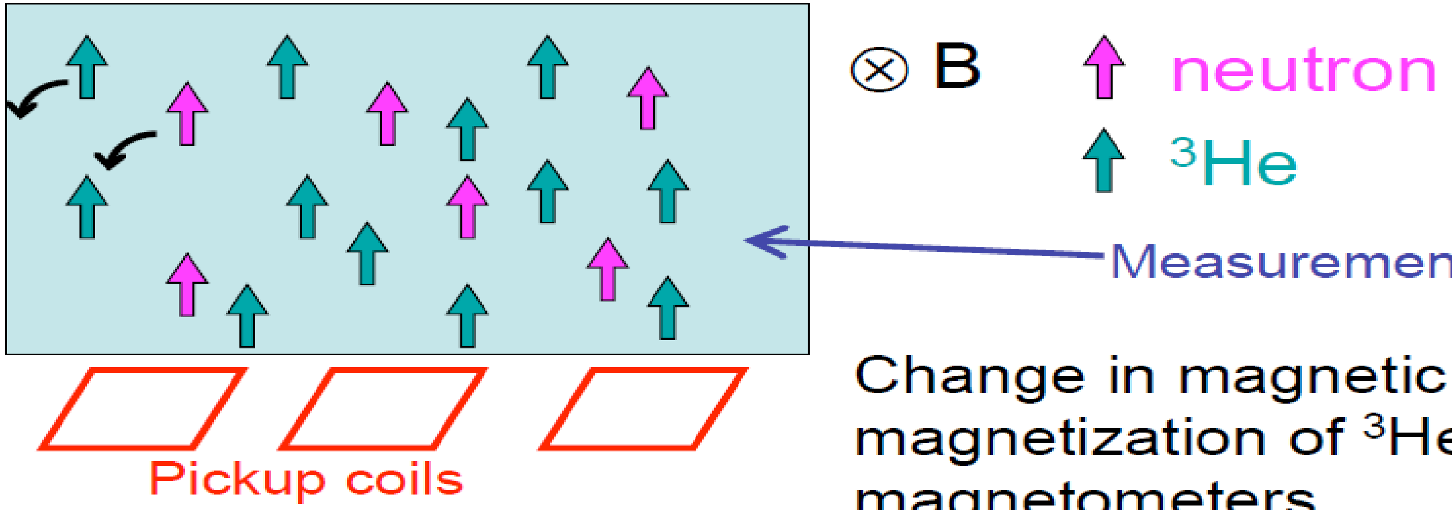
Backup Slides

Magnetometers

- Used to reduce systematics of unstable and gradient-ful (?) B fields while measuring the field.
- Have to be magnetically susceptible while having an EDM much smaller than the nEDM.
- ^{199}Hg,^{133}Cs, ^{129}Xe and ^{3}He are the most common.
- Cohabitating magnetometers are used in the same volume as the neutrons.
- Auxiliary magnetometers are used outside of the precession chamber but within the magnetic shield.

Free precession method

A dilute admixture of polarized ^{3}He atoms is introduced to the bath of SF ^{4}He ($x = N_3/N_4 \sim 10^{-10}$ or $\rho_{3He} \sim 10^{12}$/cc) as comagnetometer



Measurement cell filled with SF ^{4}He

Change in magnetic field due to the rotating magnetization of ^{3}He by SQUID magnetometers

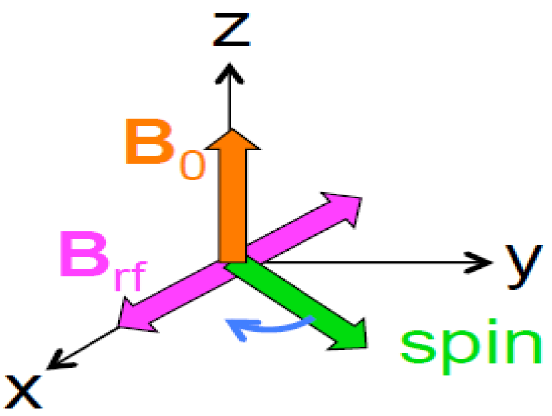
Signature of EDM appears as a shift in $\omega_3-\omega_n$ corresponding to the reversal of ***E*** with respect to ***B*** with no change in ω_3

3He concentration needs to be adjusted to maximize the sensitivity

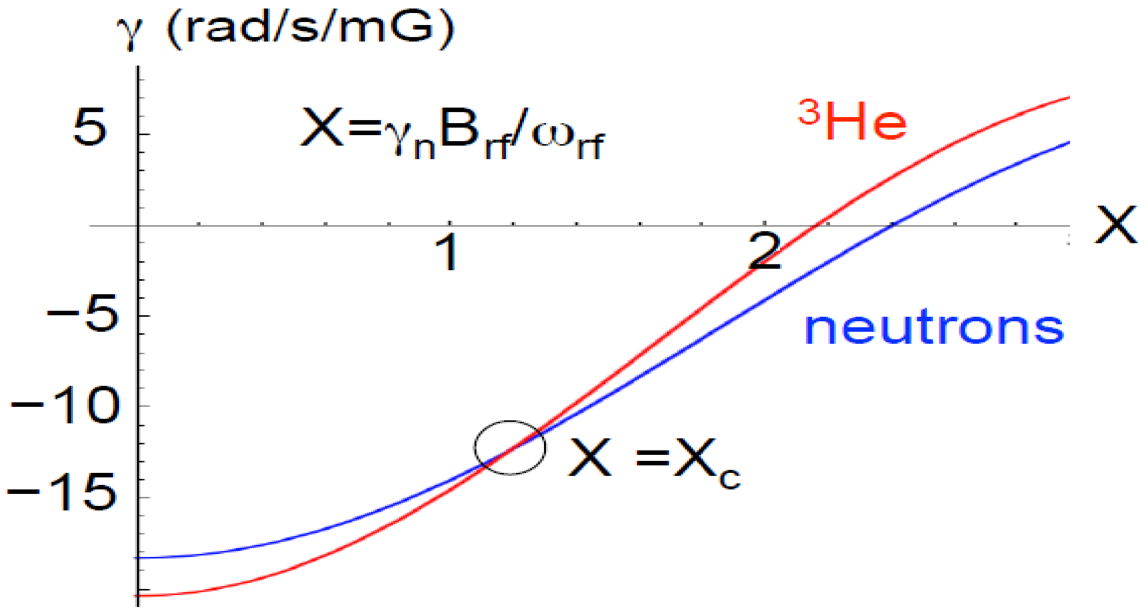
- Low concentration → small BR for capture events, weak SQUID signals
- High concentration → short storage time

Slide taken from T. M. Ito talk, nEDM workshop [LA-UR-12-25394]

Dressed spin method



A strong non-resonant RF field



B$_{rf}$ • **B**$_0$, **B**$_{rf}$ >> B$_0$, • $_{rf}$ >> • $_0$

$\overrightarrow{B_{rf}} \perp \overrightarrow{B_0}, B_{rf} \gg B_0, \omega_{rf} \gg \omega_0$

- By applying a strong non-resonant RF field, the gyromagnetic ratio can be modified or “dressed”

$$\gamma' = \gamma J_0\left(\gamma B_{rf}/\omega_{rf}\right) = \gamma J_0\left(X\right)$$

- Can tune the dressing parameter ($X = \gamma_n B_{rf}/\omega_{rf}$) until the relative precession between 3He and neutrons is zero ($X = X_c$).
- Look for X_c dependence on E field
- Provides access to EDM that is independent of variations of the ambient B-field

Slide taken from T. M. Ito talk, nEDM workshop [LA-UR-12-25394]