Neutrons and Fundamental Symmetries Experimental II: EDMs

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NNPSS

Topics I will cover:

Lecture 1: beta-decay

- A brief history of the electroweak theory---the precursor to the Standard Model.
- Neutron decay to test the V-A theory & beyond the SM interactions
- Current status with neutron experiments on gA & lifetime
- Physics is Symmetries

Lecture 2: EDM

Q: Why does EDM violate T?

- CP violation
- Electric Dipole Moments: Highly sensitive low-energy probes of new Physics
- muon- g-2

Lecture 3: other symmetry violation measurements/tests

- Baryogenesis & symmetry violations
- Nnbar oscillation: B violation
- Hadronic weak interactions: P violation
- NOPTREX: T violation
- Neutron interferometry: Lorentz symmetry violation

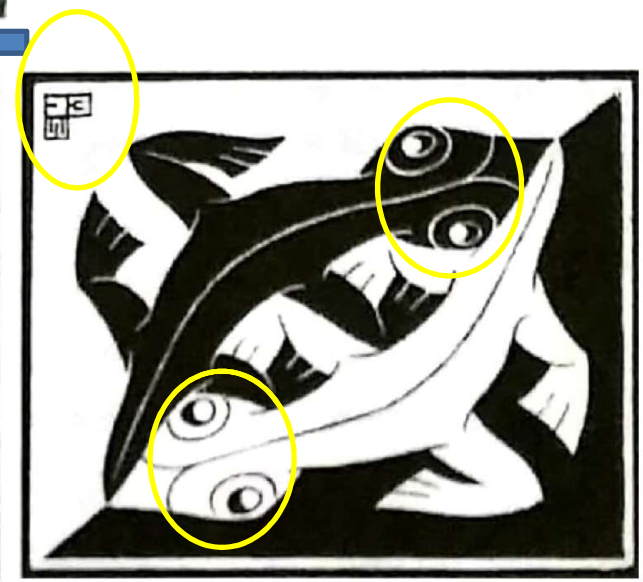
Mirror (left→right)

“Signatures of the Artist,” by S. Vigdor, Oxford University Press(2018)

Challenge: Can you find the differences (in three places) between the final and the original picture?

Mirror (up → down)

“Plane-filling motif with reptiles” by M.C. Escher

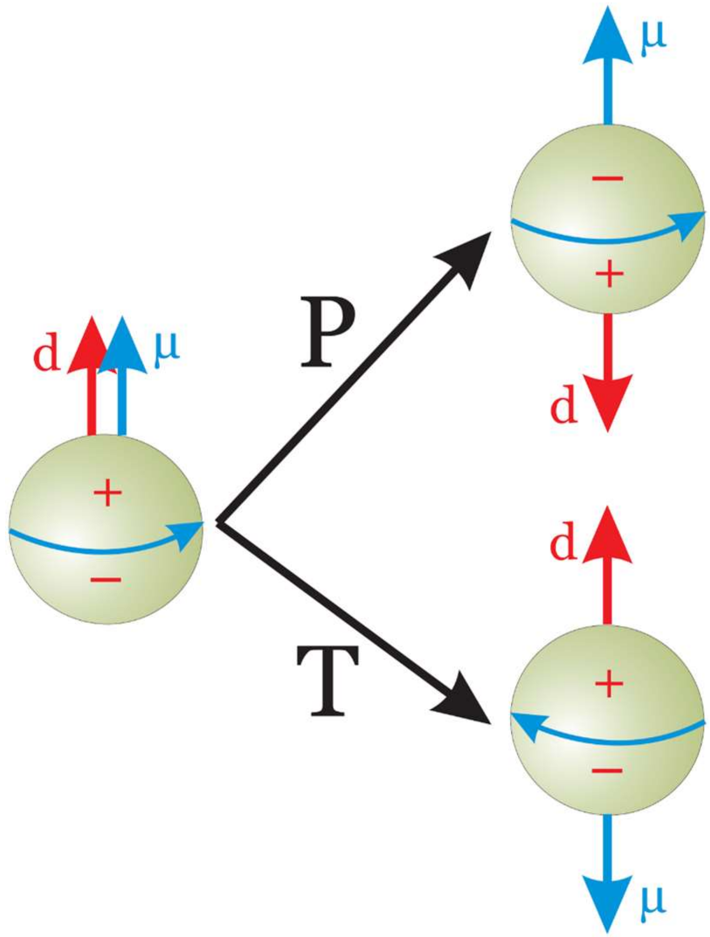


P

Black←→white

CP

CP → T

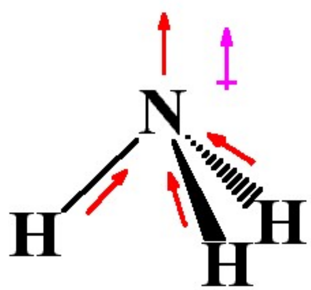


Since time symmetry requires that these time-reversed relative directions be equally probable, it requires that there be no average charge separation along the spin direction, so *the EDM must vanish*.

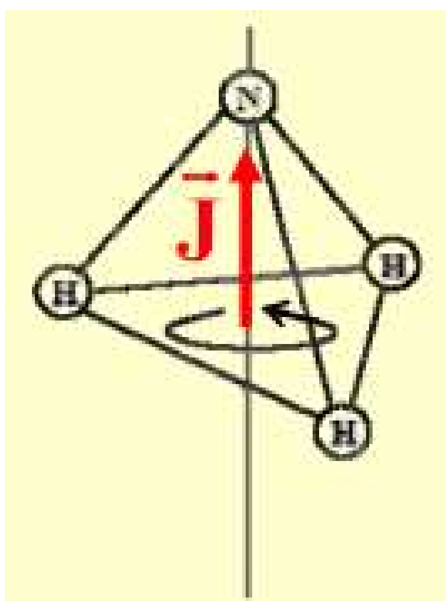
or

If an non-zero EDM is found, then the time reversal symmetry is violated, and through the CPT theorem, the CP is violated by the same amount.

Electric Dipole Moment of polar molecules

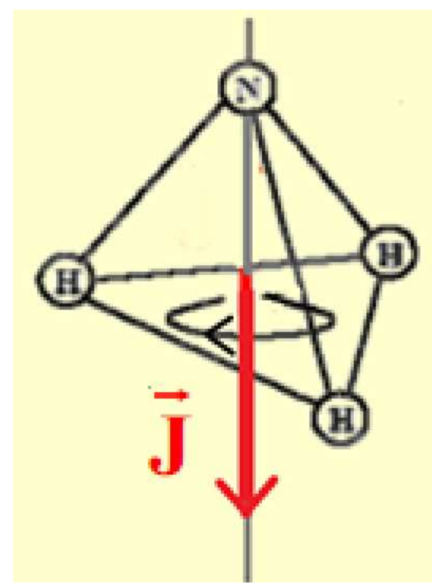


NH_3 molecule has two ground states. They are of the same energies (degenerate).



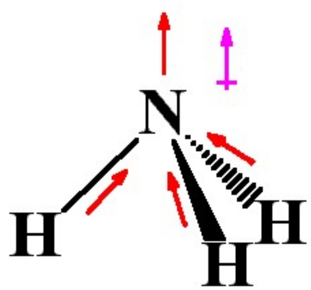
$$\vec{d} = d\,\frac{\vec{J}}{|J|}$$

Time Reversal



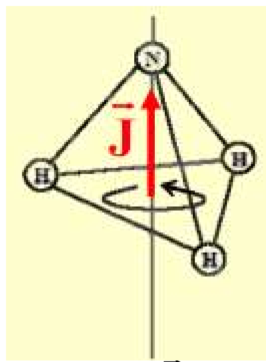
$$\vec{d} = -d\,\frac{\vec{J}}{|J|}$$

Electric Dipole Moment of polar molecules

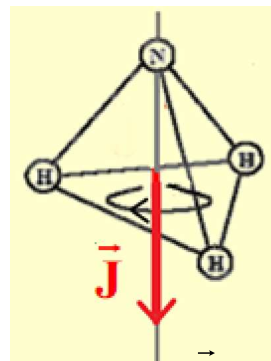


NH_3 molecule has two ground states. They are of the same energies (degenerate).

$$|\varphi_G\rangle_1 = \frac{1}{\sqrt{2}}\Big\{$$



$$+$$

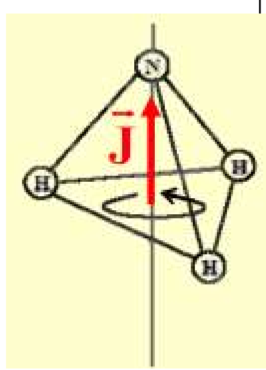


$$\Big\} \xrightarrow{T} |\varphi_G\rangle_1$$

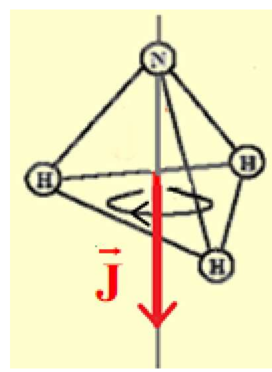
T-even

$\vec{d} = d\frac{\vec{J}}{|J|}$ $\vec{d} = -d\frac{\vec{J}}{|J|}$

$$|\varphi_G\rangle_2 = \frac{1}{\sqrt{2}}\Big\{$$



$$-$$



$$\Big\} \xrightarrow{T} -|\varphi_G\rangle_2$$

T-odd

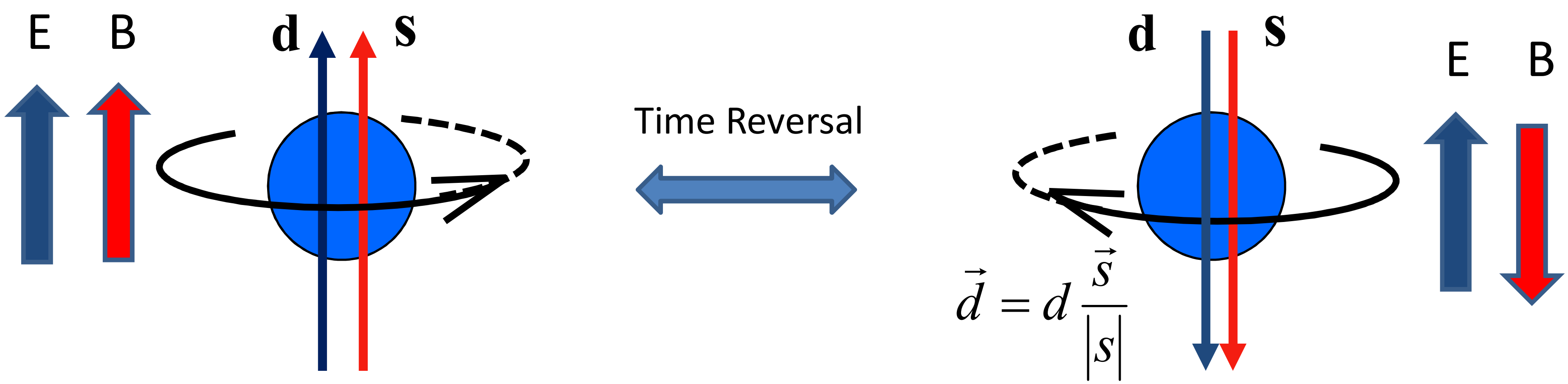
$$\Rightarrow [H, T] = 0$$

A permanent EDM is possible without violations in T (&P).

Electric Dipole Moment of fundamental particles

Fundamental particles don't have degenerate ground state, so $\vec{d} = d\hat{J}$.

Say, if the ground state (under fields) is



$$\vec{d} = d\,\frac{\vec{s}}{|s|}$$

$$\varepsilon_{1/2} = dE + \left(\frac{1}{2}\frac{\hbar}{2m}\right)B$$

$$\varepsilon_{-1/2} = -dE + \left(-\frac{1}{2}\frac{\hbar}{2m}\right)(-B)$$

T-odd Pseudo-scalar

T-even scalar

$$|\varphi_G\rangle \xrightarrow{T} |\varphi'\rangle$$

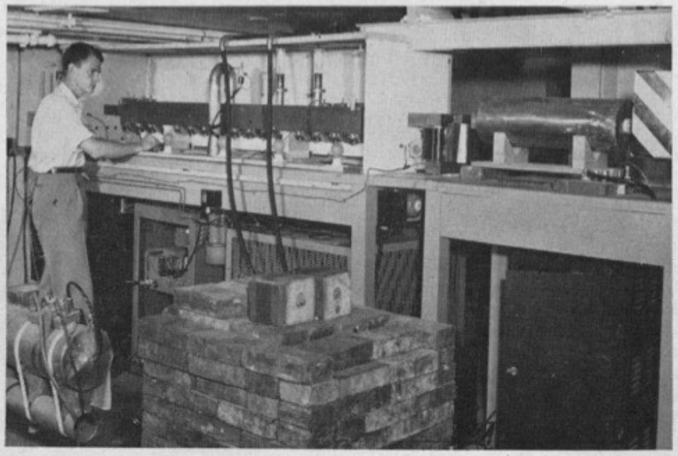
The ground state is not a T eigenstate!

$$\Rightarrow [H,T] \neq 0$$

THE NEWS
OAK RIDGE NATIONAL LABORATORY

A Publication by and for the ORNL Employees of Carbide and Carbon Chemicals Division, Union Carbide and Carbon Corporation

Vol. 3—No. 13 OAK RIDGE, TENNESSEE Friday, September 29, 1950

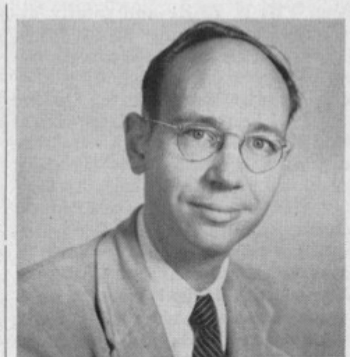


HARVARD UNIVERSITY SPONSORS PROGRAM HERE — James H. Smith, Harvard University graduate student in physics, is shown as he adjusts a neutron beam apparatus at the south face of the Oak Ridge Pile. Using the Pile as a source of neutrons, Mr. Smith is engaged in a project jointly sponsored by Harvard University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

Harvard University Conducts Important Research at ORNL

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



DR. TAYLOR

ACS Lectureship Set For October 26, 27

The East Tennessee Section of the American Chemical Society will have its Annual East Tennessee Lectureship this year in two sessions, according to plans re-

Dr. Ellison Taylor Appointed Chem. Division Director

Effective October 1, Dr. Ellison H. Taylor will assume the duties of Director of the Chemistry Division. In this capacity he will succeed Dr. John A. Swartout, who was recently elevated to the position of Assistant Research Director of Oak Ridge National Laboratory.

Dr. Taylor's present connection with the Chemistry Division is that of Associate Director of the Division and Group Leader of the Radiation Chemistry Group, in which capacities he has served since June, 1948. Previously, he had been Assistant Director of the Division, from June, 1946, to February, 1948, and was Acting Di-

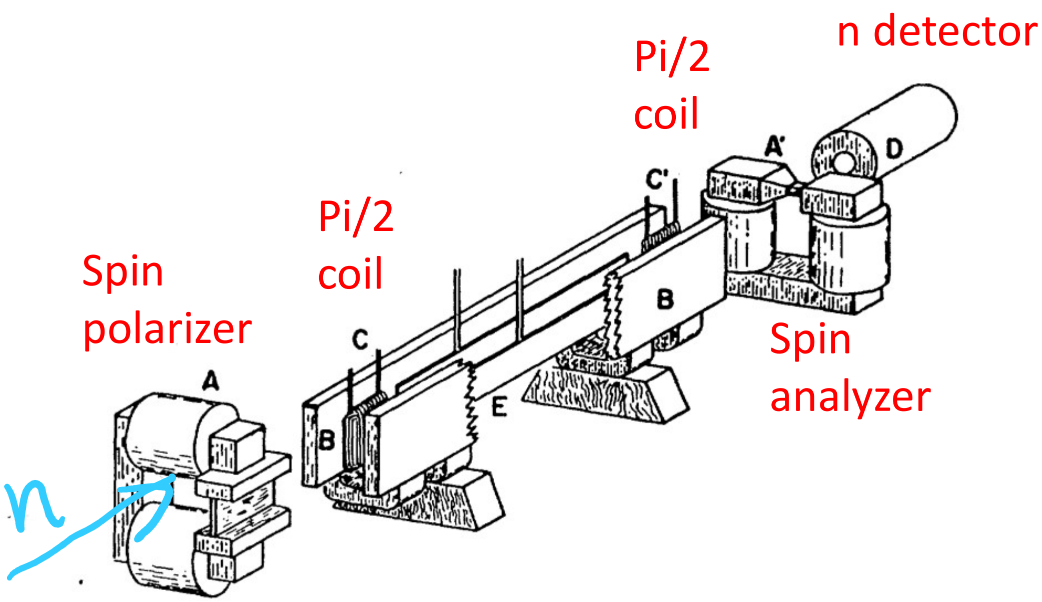
PHYSICAL REVIEW VOLUME 108, NUMBER 1 OCTOBER 1, 1957

Experimental Limit to the Electric Dipole Moment of the Neutron

J. H. Smith,* E. M. Purcell, and N. F. Ramsey
Oak Ridge National Laboratory, Oak Ridge, Tennessee, and Harvard University, Cambridge, Massachusetts

(Received May 17, 1957)

An experimental measurement of the electric dipole moment of the neutron by a neutron-beam magnetic resonance method is described. The result of the experiment is that the electric dipole moment of the neutron equals the charge of the electron multiplied by a distance $D=(-0.1\pm2.4)\times10^{-20}$ cm. Consequently, if an electric dipole moment of the neutron exists and is associated with the spin angular momentum, its magnitude almost certainly corresponds to a value of D less than 5×10^{-20} cm.



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

FIG. 1. Schematic diagram of the apparatus. A, the magnetized iron mirror polarizer. A', the magnetized iron transmission analyzer. B, the pole faces of the homogeneous field magnet. Note the horseshoe-like magnets bolted along the bottom. C, C', the coils for the radio-frequency magnetic field. D, the BF_3 neutron counter. The magnetic fields in the polarizing magnet and the homogeneous field magnet are at right angles, and two twisted iron strips were used between them to rotate the neutron spins adiabatically.

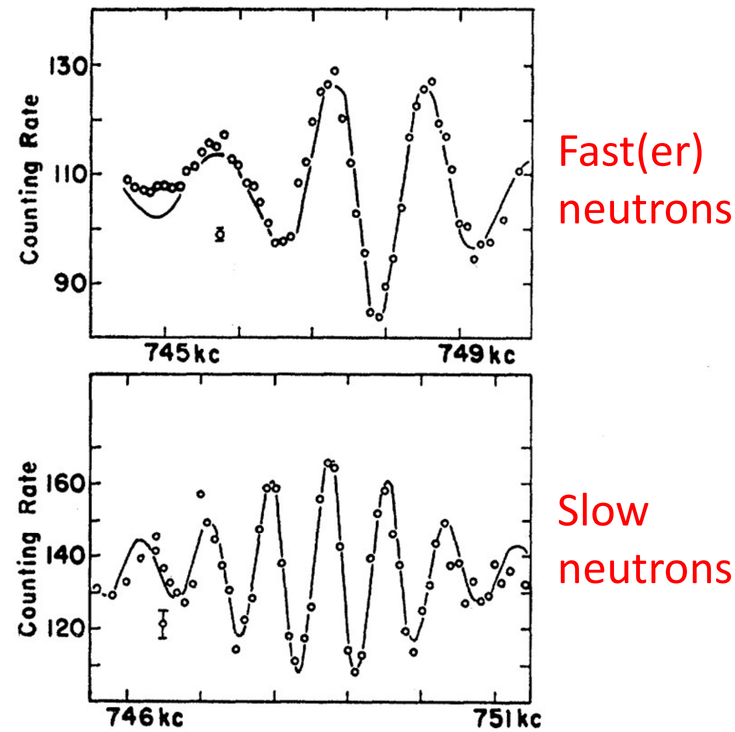
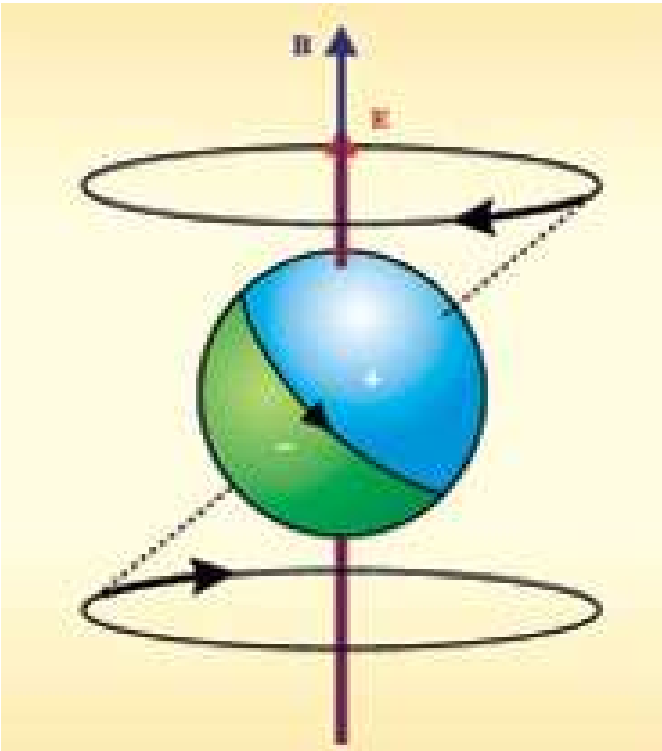


FIG. 2. Resonance curves of the neutron counting rate *versus* the frequency of the radio-frequency magnetic field. The upper curve is for a mirror angle of 3.14×10^{-3} radian, and the lower for 5.77×10^{-3} radian. A typical root-mean-square counting statistical error is shown. The lower curve shows a narrower resonance due to the fact that only slower neutrons are reflected at the larger mirror angles. It also shows more resonance detail since the polarized neutrons are more nearly monochromatic. The central peak is a minimum in the upper curve and a maximum in the lower curve since the phase of one of the coils was reversed.

Features of the separated oscillatory fields:

1. Narrow fringes
2. Not sensitive to the field uniformity.

Traditional technique: Nuclear Magnetic Resonance (NMR)



Bloch Equations:

$$\frac{dM_x(t)}{dt} = \gamma(\mathbf{M}(t) \times \mathbf{B}(t))_x - \frac{M_x(t)}{T_2}$$
$$\frac{dM_y(t)}{dt} = \gamma(\mathbf{M}(t) \times \mathbf{B}(t))_y - \frac{M_y(t)}{T_2}$$
$$\frac{dM_z(t)}{dt} = \gamma(\mathbf{M}(t) \times \mathbf{B}(t))_z - \frac{M_z(t) - M_0}{T_1}$$

Ideal cases:

(1) Free precession under a constant field, $B_z(t)=B_{0,}$ with T_1 and T_2 are long, ∞.
(2) Spin tilt (rotation) under a constant B_0 and a small perturbing oscillating field B_{rf}.

Lamor.m spin_flip.m

Traditional technique: Nuclear Magnetic Resonance (NMR)

Apply E//B, to measure EDM

$$H = -\left(\mu\vec{B} + d_n\vec{E}\right)\cdot\frac{\vec{S}}{|S|}$$

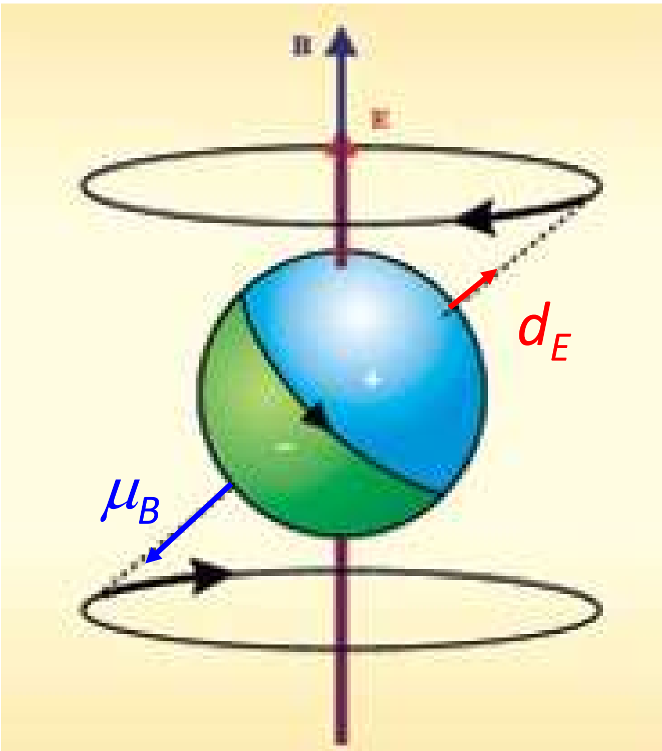


Figure: Physics Today 56 6 (2003) 33

- Larmor frequency: $\omega_B = -\frac{2\mu_B B}{\hbar}$

(~ 29.2 Hz for *B* ~ 10 mG)

- d_n: additional precession: $\omega_E = \frac{2d_n E}{\hbar}$

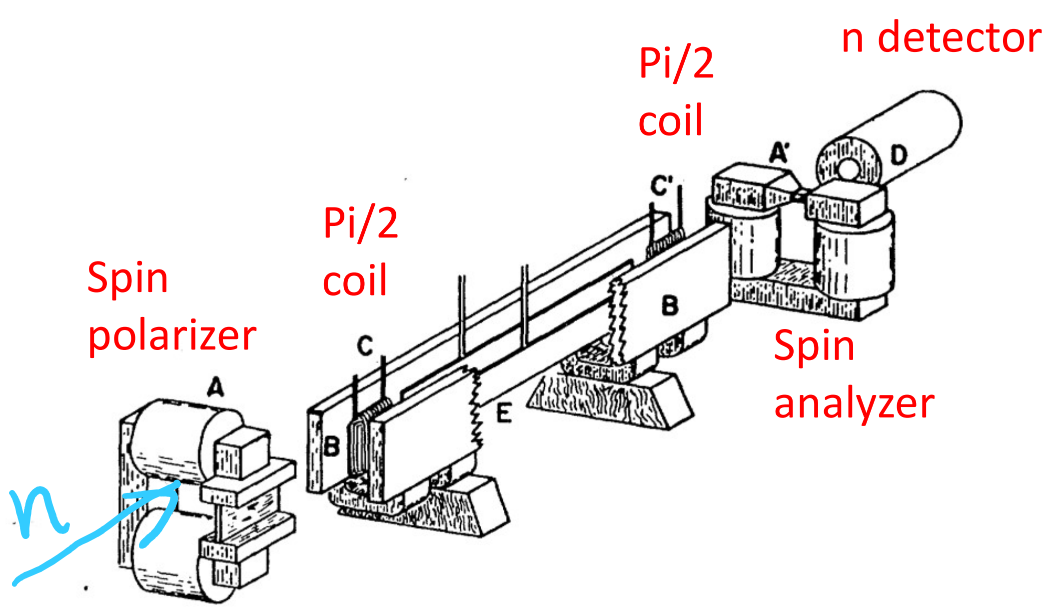
$$\omega_{E\parallel B} - \omega_{E\,anti-\parallel B} \equiv \Delta\omega = \frac{4d_E E}{\hbar}$$

- Apply static *B*, *E*||*B*
- Look for $\Delta\omega$ on reversal of *E*

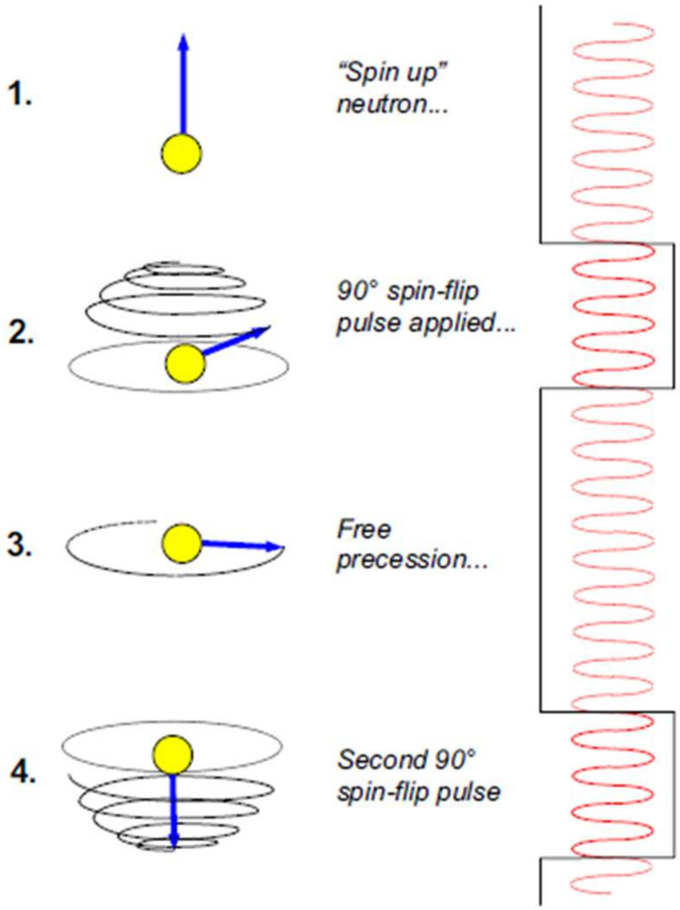
To reach d_n= 5×10^{-28} e cm, need to measure Δω=12nHz.

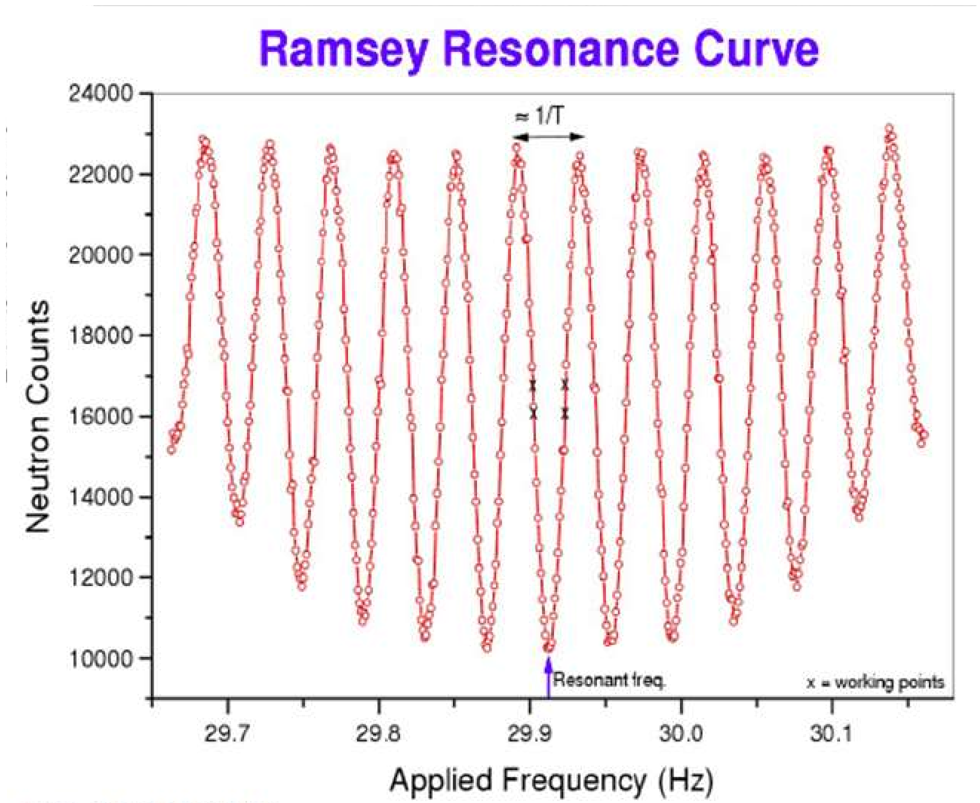
A particular arrangement that is more advantageous in many cases is one in which the oscillating field is confined to a small region at the beginning of the space in which the energy levels are being studies and to another small region at the end, there being no oscillating field in between.

-- N. Ramsey (1950)



Technique: The Ramsey's Separated Oscillatory Field Method





PRL82(1999)904

5. Spin analyzer (only allows "spin up" UCN through to be counted)

Ramsey_sequence.m

$$\psi(t) = C_p(t)\psi_p + C_q(t)\psi_q = C_p(t)\begin{bmatrix}1\\0\end{bmatrix} + C_q(t)\begin{bmatrix}0\\1\end{bmatrix}$$

$$\begin{aligned} i\hbar\dot{\psi} &= (W+V)\,\psi \\ i\hbar\begin{bmatrix}\dot{C}_p(t)\\ \dot{C}_q(t)\end{bmatrix} &= \left(\begin{bmatrix}W_p & 0\\ 0 & W_q\end{bmatrix} + \underbrace{\begin{bmatrix}0 & \hbar b e^{i\omega t}\\ \hbar b e^{-i\omega t} & 0\end{bmatrix}}_{\text{Interaction due to an external oscillating field}}\right)\begin{bmatrix}C_p(t)\\ C_q(t)\end{bmatrix}\end{aligned}$$

Interaction due to an external oscillating field

Spin flip probability (after two RF pulses, each with a duration of *τ*, and a free precession time *T in between pulses*):

Envelope

Fringes

$$P^{Ramsey}_{p,q} = |C_q|^2 = \underbrace{4\sin^2\theta\sin^2\frac{1}{2}a\tau}_{\text{Envelope}}\left(\underbrace{\cos\frac{1}{2}\lambda T\cos\frac{1}{2}a\tau - \cos\theta\sin\frac{1}{2}\lambda T\sin\frac{1}{2}a\tau}_{\text{Fringes}}\right)^2$$

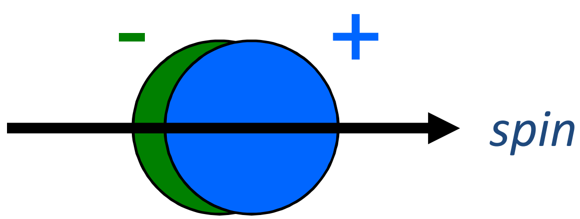
a: detuning $\quad \sin\theta = \frac{2b}{a}, \qquad \cos\theta = \frac{\omega_0 - \omega}{a}$

$$a = \sqrt{(\omega_0-\omega)^2 + (2b)^2}, \quad \text{and} \quad \omega_0 = (W_q - W_p)/\hbar.$$

$b = \gamma B_{RF}/2$: Interaction strength

Electric Dipole Moment (EDM) of the Neutron

- Neutron EDM (d_E) : Permanent, net charge separation within the neutron volume

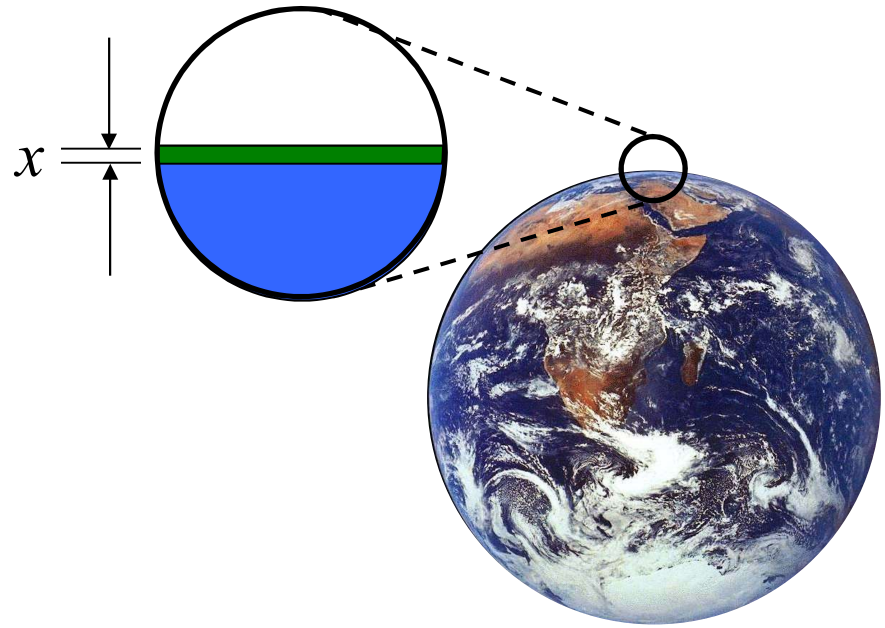


- Current limit [1]:

  $d_E < 2.9 \times 10^{-26}$ e-cm

- First experiment (1957):

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



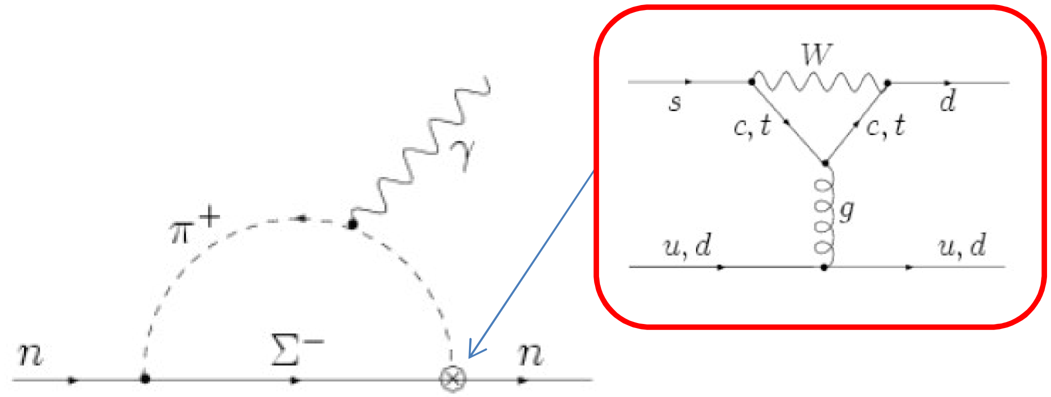
- Charge separation *x* for Earth-sized neutron:

$$x = x_{nEDM}\left(\frac{r_{Earth}}{r_n}\right) = 3\times 10^{-26}\,cm\left(\frac{6.4\times 10^{10}\,cm}{3.4\times 10^{-14}\,cm}\right) \approx 0.5mm$$

[1] PRL 97 131801 (2006)

EDM: Tests of discrete spacetime symmetries, P & T

In the Standard Model:

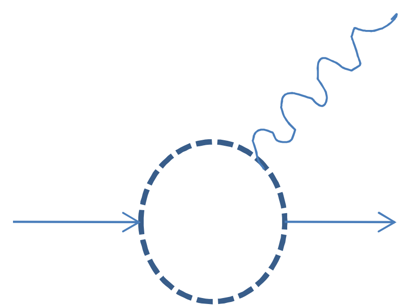


Suppressed 3-loop effect in the Standard Model

$d_n \sim 10^{-32}$ e-cm   (Khriplovich & Zhitnitsky 1986)

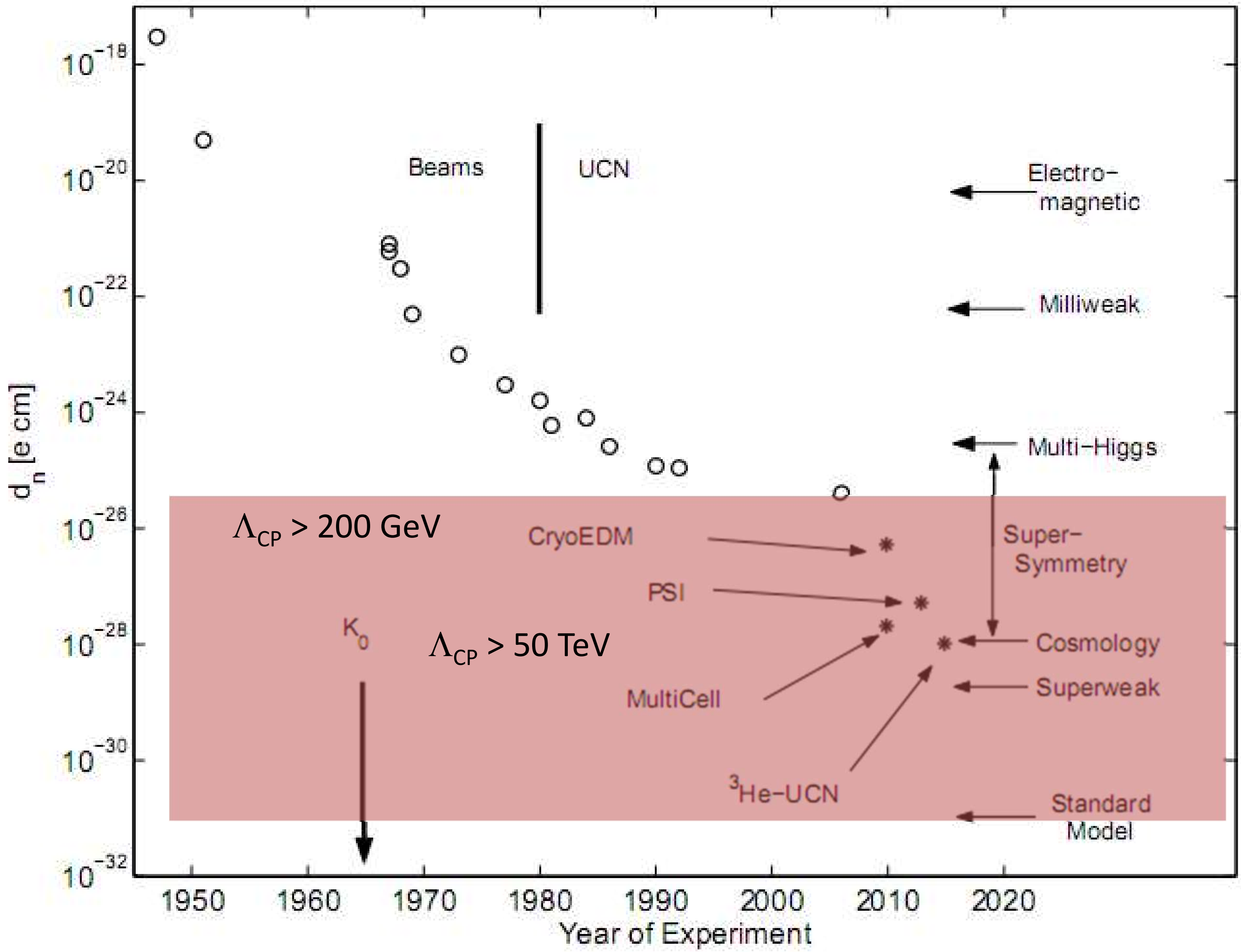
Large effect in more comprehensive theories

In Physics beyond the Standard Model:



$$d \sim (loop)\frac{m_f}{\Lambda_{cp}^{2}}$$

$d < 10^{-26}$ e-cm $\rightarrow \Lambda_{cp} = 1$ TeV



10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-28}
10^{-30}
10^{-32}
d_n [e cm]
1950
1960
1970
1980
1990
2000
2010
2020
Year of Experiment
Beams
UCN
Electro-
magnetic
Milliweak
Multi-Higgs
Super-
Symmetry
Cosmology
Superweak
Standard
Model
Λ_{CP} > 200 GeV
Λ_{CP} > 50 TeV
CryoEDM
PSI
MultiCell
^{3}He-UCN
K_0

Systematic Effects

The Motional Field + Misalignment between fields

Ramsey & Purcell (1950)
Test P violation in strong force.

First Beam Experiment

vxE motional magnetic field, $B_m = \mathbf{v} \times \mathbf{E}/c^2$

For thermal neutron beam v=1000m/s, E=100kV/cm, and B_{mot}=1mG

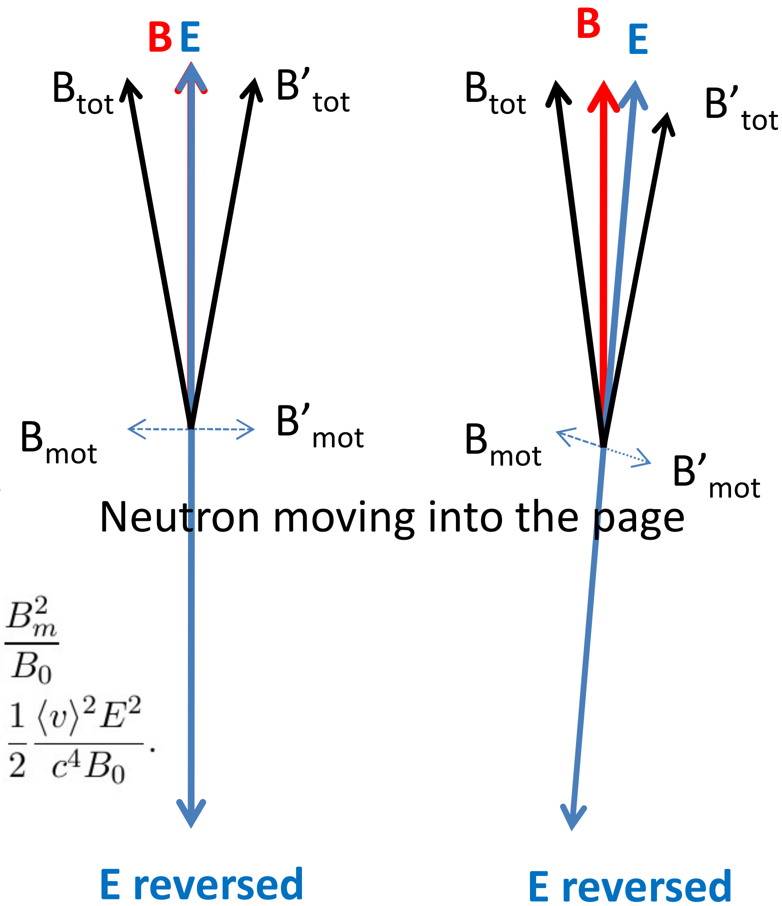
$$|B| = \sqrt{(B_0 + B_m \sin\theta_{EB})^2 + (B_m \cos\theta_{EB})^2} \approx B_0 + \theta_{EB} B_m + \frac{1}{2}\frac{B_m^2}{B_0}$$
$$= B_0 + \frac{\theta_{EB}\langle v\rangle E}{3c^2} + \frac{1}{2}\frac{\langle v\rangle^2 E^2}{c^4 B_0}.$$

$$\Delta\omega = \frac{\gamma\theta_{\mathrm{EB}} v}{c} E + \frac{\gamma v^2}{2c^2}\frac{E^2}{B_0}$$

$\theta_{EB} < 10^{-5}$ radians for 10^{-24} e-cm measurement

This led to UCN storage cell experiment
V_{ucn}=5m/s
In addition, <v>=0 in a cell

Ideally, In reality,



$|B_{tot}| = |B'_{tot}|$
upon field reversal

$|B_{tot}| \neq |B'_{tot}|$
$\Delta\omega \neq 0$

θ_{EB} =0.5° for nEDM
Field reversal to 10% accuracy.

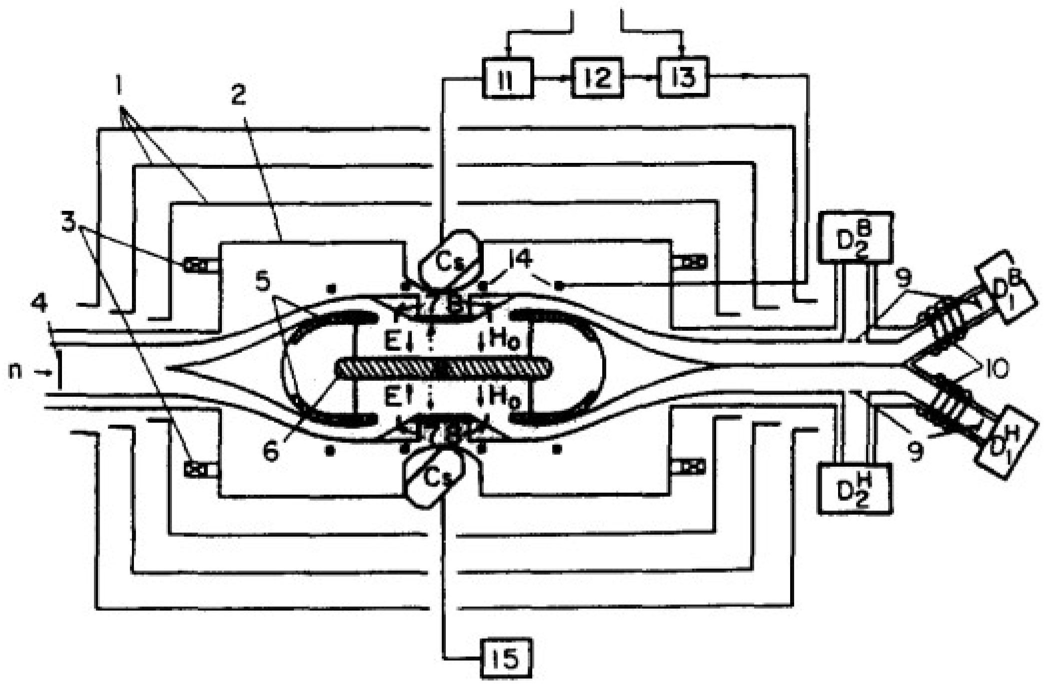
ILL Experiment (now improved at PSI):

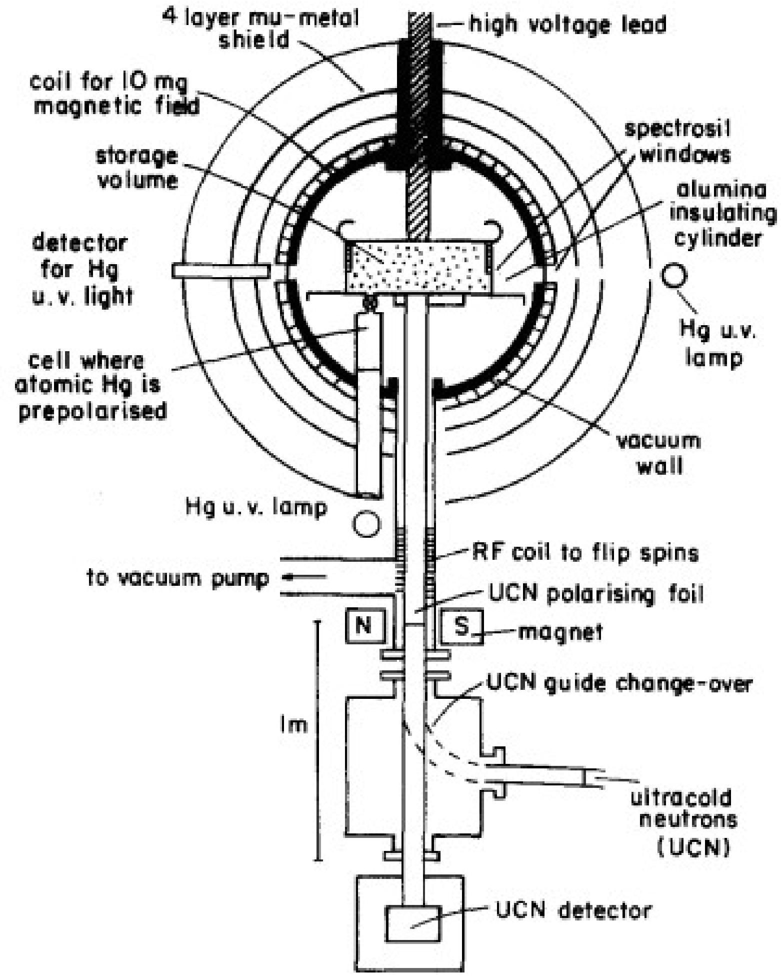
- UCN in storage cell (Be electrode, BeO dielectric cell wall) at room temperature
- Ramsey's separate oscillatory field method (interference in time domain)

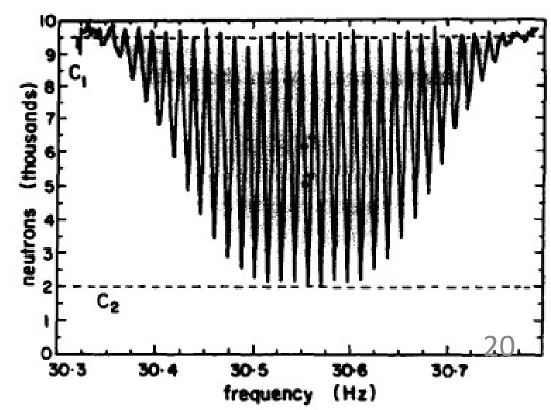
PNPI Experiment:

Double cell configuration

$\rightarrow$ double the signal and reduce the sensitivity to common mode magnetic field noise







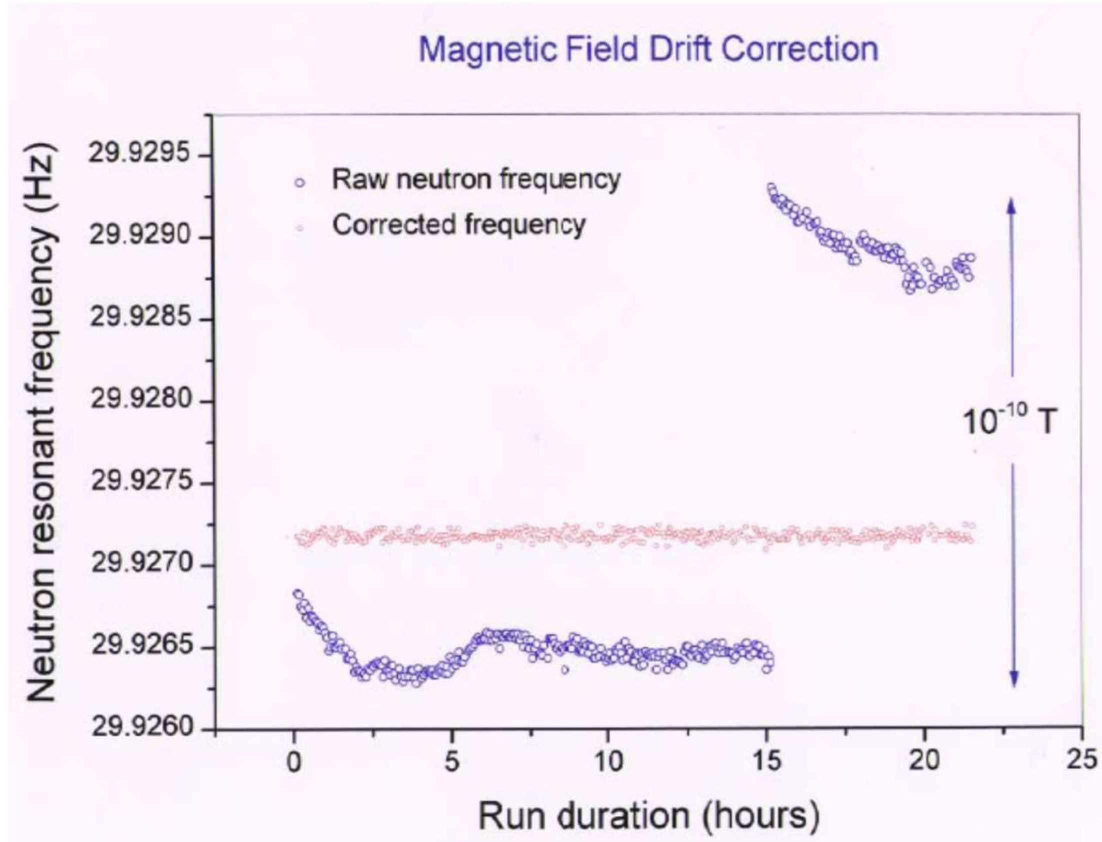
Magnetic Field Fluctuations, Corrected by "Co-magnetometer"

If nEDM = 10^{-26} e·cm,

10kV/cm $\rightarrow$ 0.1 μHz uncertainty

$\cong$ B field of 2×10^{-15} T.

"Co-magnetometer"
Uniformly samples the B Field faster than its relaxation time.



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

EDM of ^{199}Hg < 10^{-29} e-cm (measured); atomic EDM ~ $\alpha^2 Z^2 \rightarrow {}^3$He EDM << 10^{-30} e-cm

Ramsey-Bloch-Siegert (RBS) Shift (due to a second oscillating field)

In a typical NMR setup, which has a main holding field B0 and one RF source driven in the resonant frequency $\omega = \gamma B_0 = \omega_0$, the presence of another RF source with a different frequency, could shift the resonant frequency.

In the co-rotating frame of the second RF source (with an amplitude B_2 and frequency ω_2:

$$B^{eff} = \sqrt{(B_0 - \omega_2/\gamma)^2 + B_2^2}$$

When in resonance, the frequency of the original RF source (relative to ω_2) becomes

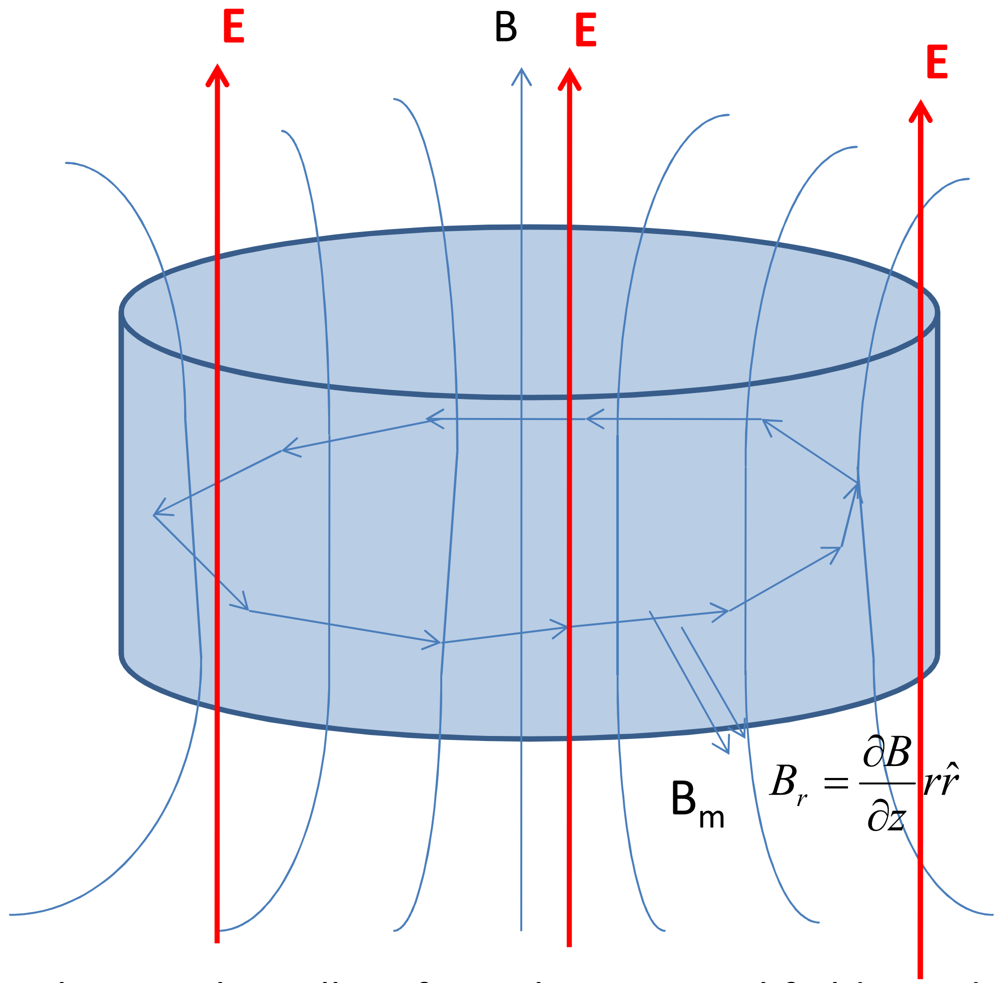
$$\omega - \omega_2 = \gamma B^{eff} = \sqrt{(\omega_0 - \omega_2)^2 + (\gamma B_2)^2}$$

$$\approx (\omega_0 - \omega_2) + \frac{1}{2}\frac{(\gamma B_2)^2}{\omega_0 - \omega_2},$$

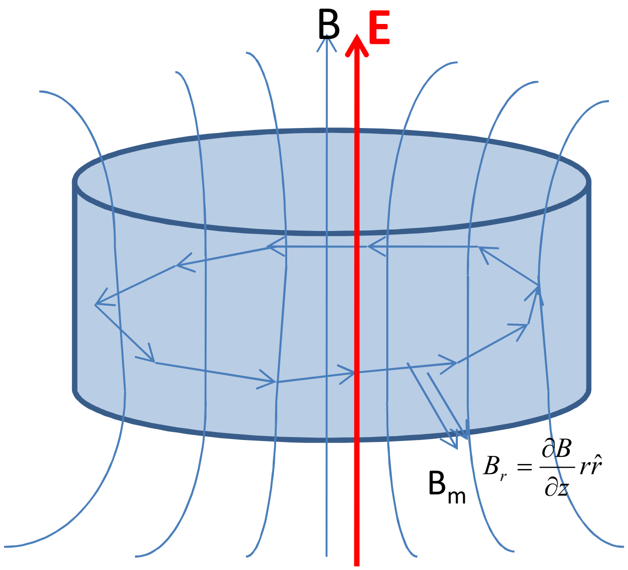
Back in the lab frame, the resonant frequency becomes

$$\omega = \omega_0 + \frac{1}{2}\frac{(\gamma B_2)^2}{\omega_0 - \omega_2}.$$

Geometric Phase (additional phase due to the specific path)



For a trajectory very close to the cell surface, the motional field is radially outward (inward). In the neutron's co-moving frame, the neutrons experience an effective rotating field, which is a linear combination of the motional field B_m and a radial field $B^r = -(\partial B_0^z/\partial z)(R/2)$ due to a non-zero gradient of the holding field.



This rotating field will cause the RBS frequency shift:

$$\omega_{\circlearrowright}^{\uparrow\uparrow} = \omega_0 + \frac{1}{2}\frac{\gamma^2(B^r + B_m)^2}{\omega_0 - \omega_r}, \text{ and}$$
$$\omega_{\circlearrowleft}^{\uparrow\uparrow} = \omega_0 + \frac{1}{2}\frac{\gamma^2(B^r - B_m)^2}{\omega_0 + \omega_r},$$

for CW and CCW motion, respectively.

For equal probability of CW and CCW motions, the averaged frequency shift is

$$\Delta\omega^{\uparrow\uparrow} = \frac{\Delta\omega_{\circlearrowright}^{\uparrow\uparrow} + \Delta\omega_{\circlearrowleft}^{\uparrow\uparrow}}{2} = \frac{1}{4}\frac{\gamma^2(B^r + B_m)^2}{\omega_0 - \omega_r} + \frac{1}{4}\frac{\gamma^2(B^r - B_m)^2}{\omega_0 + \omega_r}.$$

Upon E field reversal, the frequency shift is

$$\Delta\omega^{\uparrow\downarrow} = \frac{1}{4}\frac{\gamma^2(B^r - B_m)^2}{\omega_0 - \omega_r} + \frac{1}{4}\frac{\gamma^2(B^r + B_m)^2}{\omega_0 + \omega_r}.$$

The difference between field reversal:

$$\Delta\omega^{\uparrow\uparrow} - \Delta\omega^{\uparrow\downarrow} = \frac{\gamma^2 B^r B_m}{\omega_0 - \omega_r} - \frac{\gamma^2 B^r B_m}{\omega_0 + \omega_r} = \gamma^2 B^r B_m \frac{2\omega_r}{\omega_0^2 - \omega_r^2}$$
$$= 2\gamma^2 B^r \frac{v_\perp E}{c^2}\frac{v_\perp/R}{\omega_0^2 - \omega_r^2} = -\frac{\partial B_0^z/\partial z}{B_0^2}\frac{(v_\perp/c)^2}{1-(\omega_r/\omega_0)^2}E.$$

Gravitational Shift between UCN and Comagnetometers

The comagnetometer atoms and UCN have different thermal energies. There is a gravitational displacement between them. Under a field gradient, the ratio of the volume-averaged magnetic field experience by the UCN and that by the co-magnetometer is

$$R_a^{\uparrow} = \frac{B_0^n}{B_0^{Hg}} = \frac{\overline{B}_0 - \Delta h \langle \frac{\partial B}{\partial z} \rangle_V}{\overline{B}_0} = 1 - \Delta h \frac{\langle \frac{\partial B}{\partial z} \rangle_V}{B_0},$$

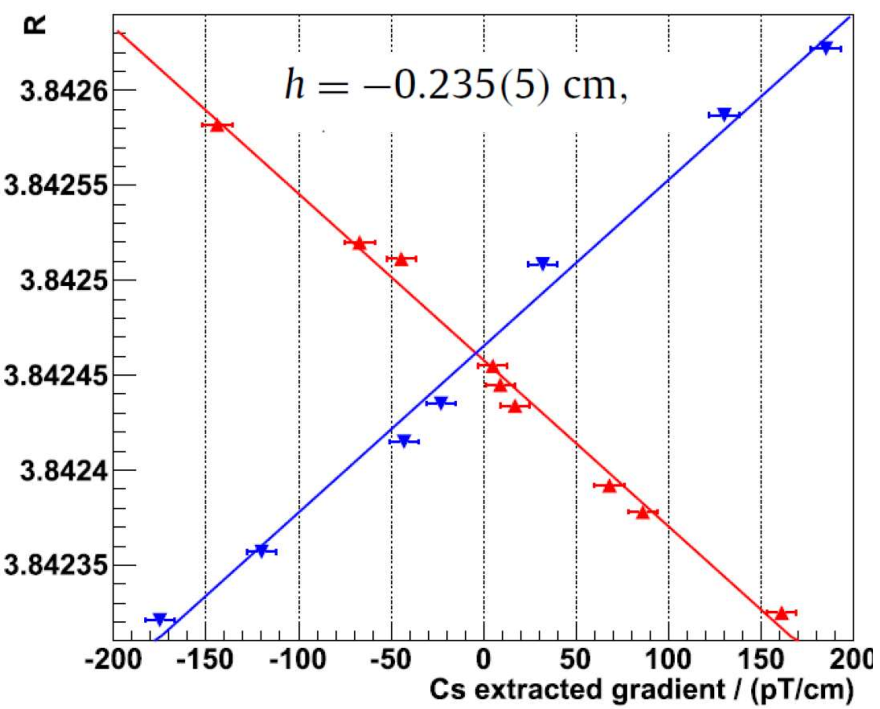
$$R_a^{\downarrow} = \frac{B_0^n}{B_0^{Hg}} = \frac{\overline{B}_0 + \Delta h \langle \frac{\partial B}{\partial z} \rangle_V}{\overline{B}_0} = 1 + \Delta h \frac{\langle \frac{\partial B}{\partial z} \rangle_V}{B_0},$$

$$= \left| \frac{\nu_n}{\nu_{Hg}} \frac{\gamma_{Hg}}{\gamma_n} \right|$$

Measurement of this ratio under B-field reversal can be used to extract Δh.

The crossing point has zero gradient!
(Do EDM measurements at the crossing point to control the GP effect.)

S. Afach *et al.*,
Phys. Lett. B **739**, 128 (2014)



Earth Rotation

11.6 μ Hz

The rotation of the earth gives an extra torque to the spin of the neutrons:

$$\frac{d\vec{S}}{dt} = \vec{\omega}_{\oplus} \times \vec{S},$$

If B field is applied vertically ↑, then the frequency of the spin precession is

$$|\Omega^{\uparrow\downarrow}| = \sqrt{(\Omega_0 \cos\phi)^2 \pm (\Omega_0 \sin\phi + \omega_{\oplus})^2} \approx \Omega_0 \pm \omega_{\oplus} \sin\phi + \frac{1}{2}\frac{\omega_{\oplus}^2}{\Omega_0}$$

The diff. frequency upon B field reversal is $\Delta\Omega = 2\omega_{\oplus} \sin\phi.$

$$R_a^{\uparrow\downarrow} = \frac{B_0^n}{B_0^{Hg}} = \left| \left(\frac{\nu_n \pm \omega_{\oplus}/2\pi \sin\phi}{\nu_{Hg} \pm \omega_{\oplus}/2\pi \sin\phi} \right) \left(\frac{\gamma_{Hg}}{\gamma_n} \right) \right|$$

$$= \left[1 \pm \Delta h \frac{\langle \frac{\partial B}{\partial z} \rangle}{B_0} \right] \pm \frac{\omega_{\oplus}/2\pi \sin\phi}{B_0} \left[\frac{1}{|\gamma_{Hg}|} + \frac{1}{|\gamma_n|} \right]$$

The gravitational displacement:

$$\Delta h \frac{\langle \frac{\partial B}{\partial z} \rangle}{B_0} = \pm(R_a - 1) - \frac{\omega_{\oplus}/2\pi \sin\phi}{B_0} \left[\frac{1}{|\gamma_{Hg}|} + \frac{1}{|\gamma_n|} \right]$$

The false EDM:

$$d^{meas} = d_n + k \frac{R_a^{\uparrow} - R_a^{\downarrow}}{2} = d_n - k \frac{\omega_{\oplus}/2\pi \sin\phi}{B_0} \left[\frac{1}{|\gamma_{Hg}|} + \frac{1}{|\gamma_n|} \right]$$

Pseudomagnetic Field (due to comagnetometer)

^{199}Hg comagnetometers are spin polarized. Both ^{199}Hg and n have spin ½. They can scatter coherently and incoherently, with the cross-sections:

$$a_{coh}^2 = \frac{1}{16}(3a_+ + a_-)^2 = \frac{36(2)\ \mathrm{b}}{2\pi} = (16.9(4)\ \mathrm{fm})^2$$
$$a_{inc}^2 = \frac{3}{16}(a_+ - a_-)^2 = \frac{30(3)\ \mathrm{b}}{2\pi} = (\pm 15.5(8)\ \mathrm{fm})^2$$

We can solve the spin-dependent scattering length:

$$a_+ = 25.85\ (\text{or } 7.95)\ \mathrm{fm}$$
$$a_- = -9.95\ (\text{or } 43.75)\ \mathrm{fm}.$$

The spin-dependent interaction leads to different potentials:

$$\Delta U = U_+ - U_- = \frac{2\pi\hbar^2}{m_n}\langle n\rangle(a_+ - a_-) \quad \rightarrow \quad \Delta\nu = \Delta U/h = 5000\ \mu\mathrm{Hz}$$

for Hg pressure of 1e-5 torr→ pseudomagnetic field of 20 pT.

The field is perp to B_0 & unchanged with E field reversal.

However, fluctuations in pressure and the polarization angle can cause additional frequency fluctuation beyond the required precision.

$$\frac{2.5\ \mu\mathrm{Hz}}{5000\ \mu\mathrm{Hz} \times (1 \pm \Delta p/p)} = P_z^{Hg} = \cos(\pi/2 \pm \epsilon) \approx \epsilon.$$

10% 0.5%

Also, the precession of 199Hg (7Hz in 10 mG) causes the RBS shift of

$$\Delta\omega = \frac{1}{2}\frac{(\gamma H_2)^2}{\omega_0 - \omega} = \frac{1}{2}\frac{(5000\mu\mathrm{Hz})^2}{30\mathrm{Hz} - 7\mathrm{Hz}} = 0.6\mu\mathrm{Hz}.$$

Experiment expects record figure of merit

EDM Energy shift: $\Delta U = \hbar\, \Delta\omega_E = 4\, d_E\, E$

Uncertainty principle: $\Delta U \Delta t > \hbar$
(Δt = measurement time)

$$d_E \sim \frac{\hbar}{4\Delta t E}$$

Repeat with N neutrons:

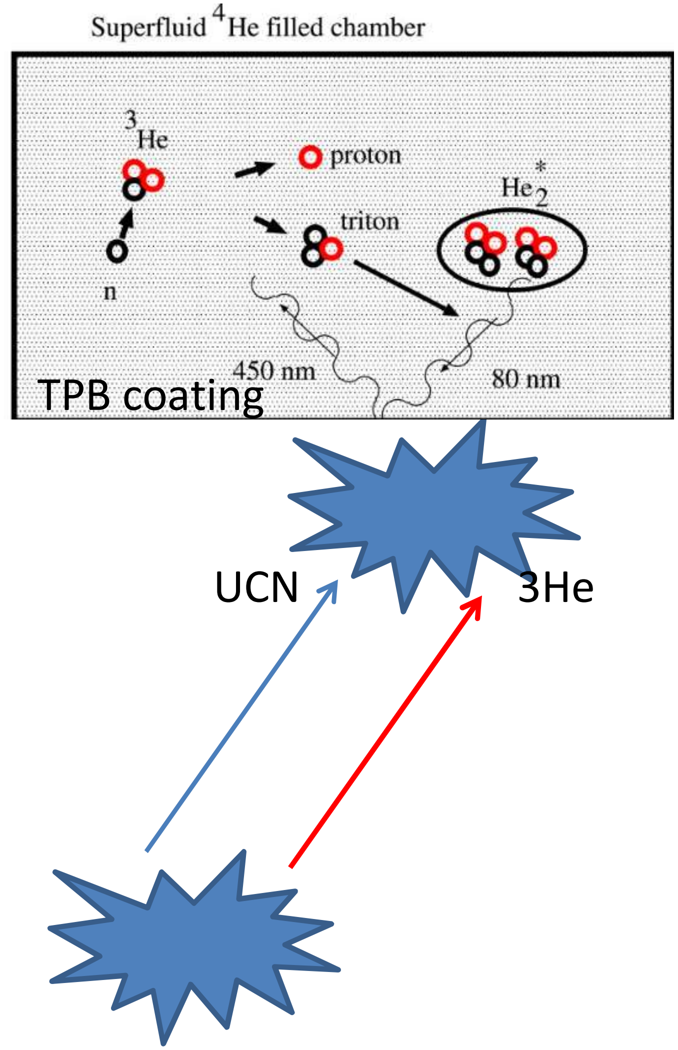
$$d_E \sim \frac{\hbar}{4\Delta t E\sqrt{N}}$$

	N	Δt	E	d_E
Previous (ILL)	~10^8 (UCN from reactor)	130 s (UCN in vacuum)	5 kV/cm (across vacuum)	< 3×10^{-26} e-cm
SF LHe	~3×10^{10} (spallation, superthermal UCN)	~ 500 s (UCN in LHe)	50 kV/cm (across LHe)	~ 10^{-28} e-cm

Experiment uses ^{3}He as detector

R. Golub and S. K. Lamoreaux, Phys. Rep. 237 (1994) 1

- UCN too dilute to detect with magnetometer (SQUID)
- Inject small concentration (~ 10^{-11}) of polarized ^{3}He
- Look for reaction: n + ^{3}He → t + p + 764 keV
  - t, p scintillate in ^{4}He
  - Pipe through light guides and detect with PMT



- n + ^{3}He → t + p:

  σ (^{3}He, n: ↑↓singlet) ~ 10^7 b

  σ (^{3}He, n: ↑↑ triplet) < 10^4 b

- μ_{He}/μ_n = 1.11

  ^{3}He spins will rotate ahead of n spins in same *B*

Scintillation light according to $\Phi = \Phi_0 \sin(\omega_{He} - \omega_n)\, t \sim 1 - P_n P_3 \cos(\omega_{He} - \omega_n) t$

- Independent monitor of ^{3}He spins with SQUIDs

Features of the new SNS nEDM experiment:

- Double cell (common B, opposite E)

- Ultra-cold neutrons produced in-situ
  - in superfluid Helium below 0.7K to achieve long storage time (suppress phonon upscattering) **as a UCN source**

- Helium-3 as co-magnetometer
  - precession monitored by SQUID
  - long relaxation time in superfluid Helium **as a buffer gas**

- Neutron precession measured through the spin-dependent n+^{3}He capture reaction **as a particle detector**
  - Use liquid helium as scintillating medium
  - Cell has to be optically transparent as a part of the light guide
  - PMT operated at cryogenic temperatures (4K)

as a HV insulator

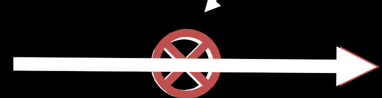
- High dielectric strength of superfluid helium (>50kV/cm)

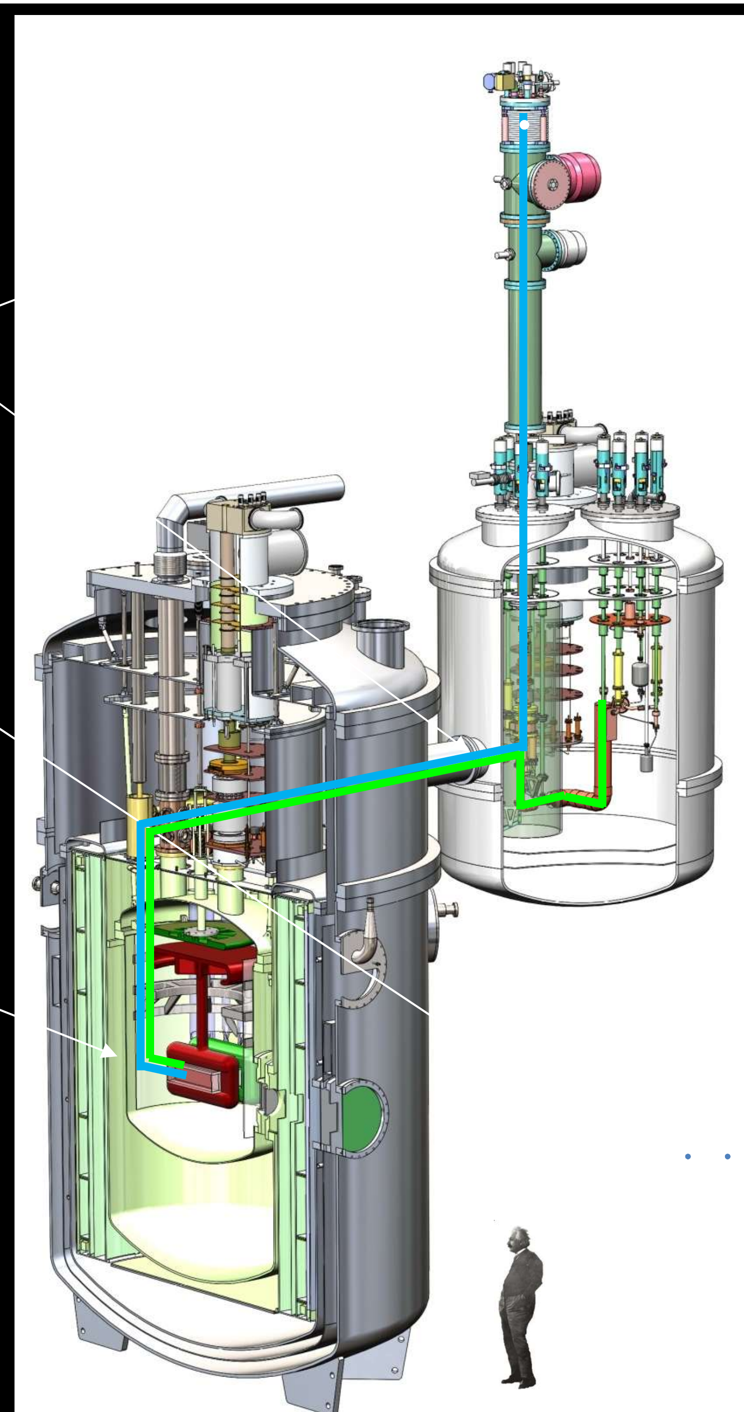
Look at me!
Look at me!
Look at me NOW!
It is fun to have fun
but you have to know how.

I can hold up the cup
and the milk and the cake!
I can hold up these books!
and the fish on a rake!
I can hold the toy ship
and a little toy man!
And look! With my tail
I can hold a red fan!
I can fan with the fan
As I hop on the ball!
but that is not all.
Oh, no
That is not all…

nEDM@SNS
Measurement Cycle

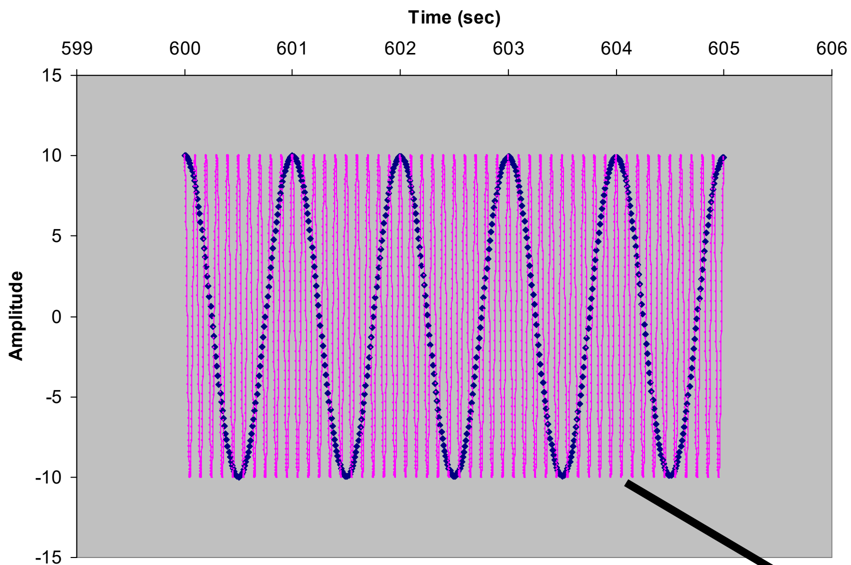
1. Load collection volume with polarized ^{3}He atoms
2. Transfer polarized ^{3}He atoms into measurement cell
3. Illuminate measurement cell with polarized cold neutrons to produce polarized UCN
4. Apply a $\pi/2$ pulse to rotate spins perpendicular to B_0
5. Measure precession frequency
6. Remove reduced polarization ^{3}He atoms from measurement cell
7. Flip E-field & Go to 1.

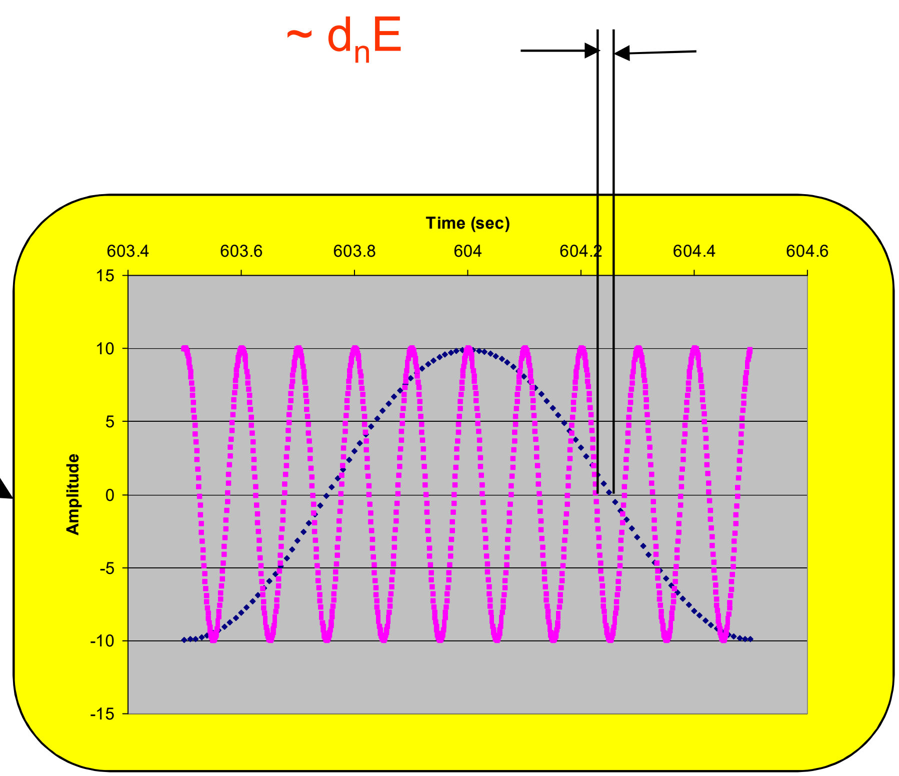




Slide thanks to Vince Cianciolo

THE SIGNAL





$^3He(n,p)t$ Scintillation Light

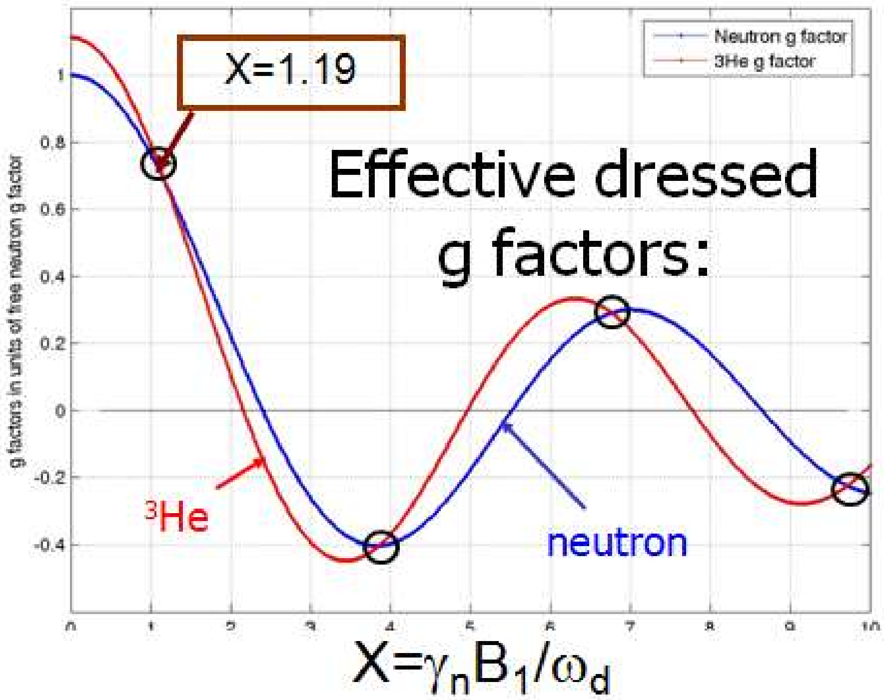
$\nu \sim (\gamma_3 - \gamma_n)$

SQUID $\nu \sim \gamma_3$

Dressed Spin Magnetometry

Dressed_spin.m
Dressed_spin2.m

The magnetic moment of 3He can be altered through “spin dressing” with applied RF:



$$\gamma' = \gamma J_0(\gamma B_{RF}/\omega_{RF}) = \gamma J_0(x)$$

The difference in the precession frequency between neutron and 3He:

$$\delta\omega = \left[\gamma_n J_0(\gamma_n x) - \gamma_3 J_0(\gamma_3 x)\right]$$

= 0 with appropriate x

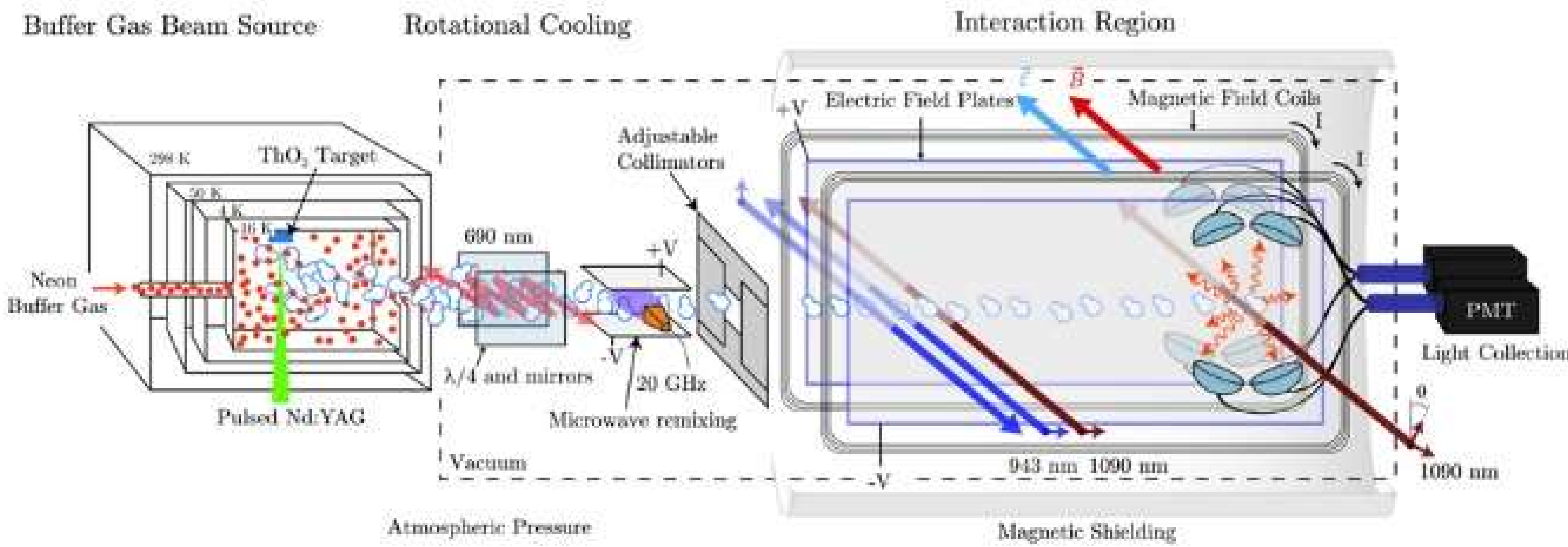
1kHz, 100 mG RF field

All systematic effects and noises associated with the external magnetic field disappear!

EDM observable: $$\delta\omega = 2 d_n E J_0(\gamma_n x)$$

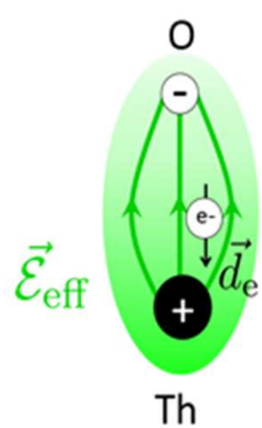
modulate *X* to look for X_c which leads to $\delta\omega$=0

ACME experiment

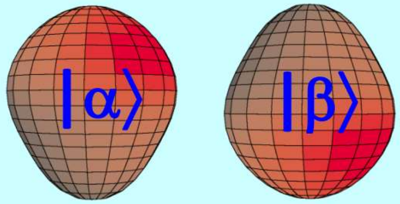


$d_e = (-2.1 \pm 3.7_{stat} \pm 2.5_{syst}) \times 10^{-29}\ e \cdot \mathrm{cm}$

Science 17 Jan 2014:
Vol. 343, Issue 6168, pp. 269-272



10 V/cm → 10*1e+9 V/cm,



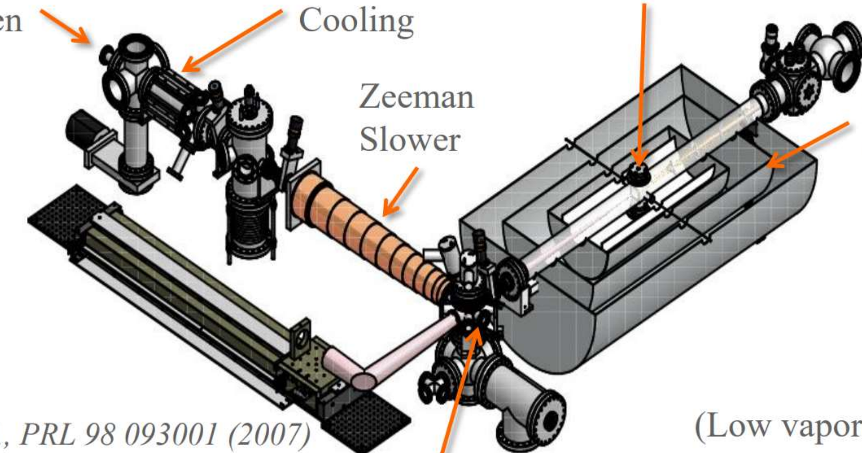
A large quadrupole and
octupole deformation results
In an enhanced Schiff moment
– Auerbach, Flambaum & Spevak (1996)

Enhancement Factor: EDM (^{225}Ra) / EDM (^{199}Hg)

Skyrme Model	Isoscalar	Isovector	Isotensor
SIII	300	4000	700
SkM*	300	2000	500
SLy4	700	8000	1000

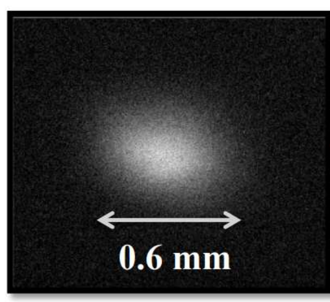
Collect Atoms in MOT

Radium-255
deformed nuclei



J. R. Guest et al., PRL 98 093001 (2007)

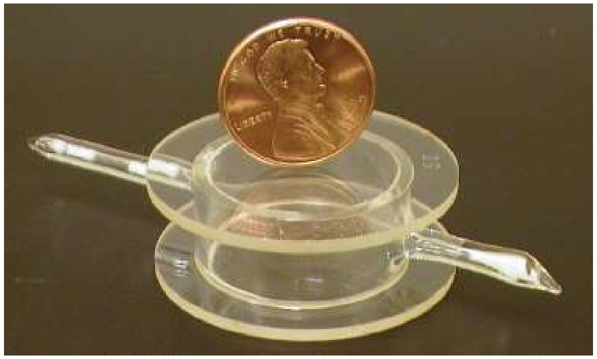
(Low vapor pressure)

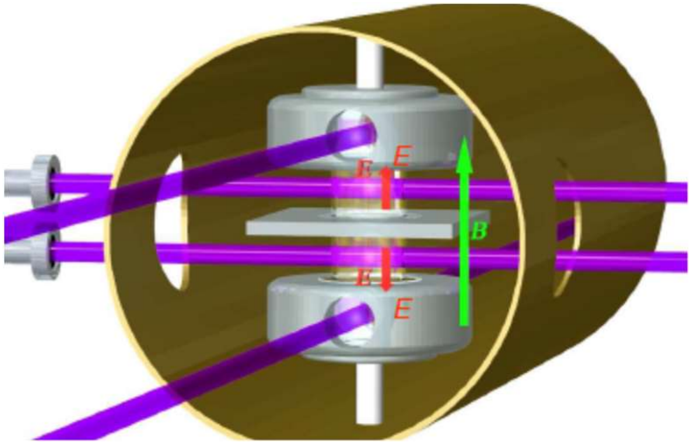


^{226}Ra MOT
20,000 atoms

For EDM:	For Testing:
Ra-225	Ra-226
I = 1/2, J = 0	I = 0, J = 0
$t_{1/2}$ = 15 days	$t_{1/2}$ = 1600 yrs

The Seattle ^{199}Hg (atomic) EDM Measurement



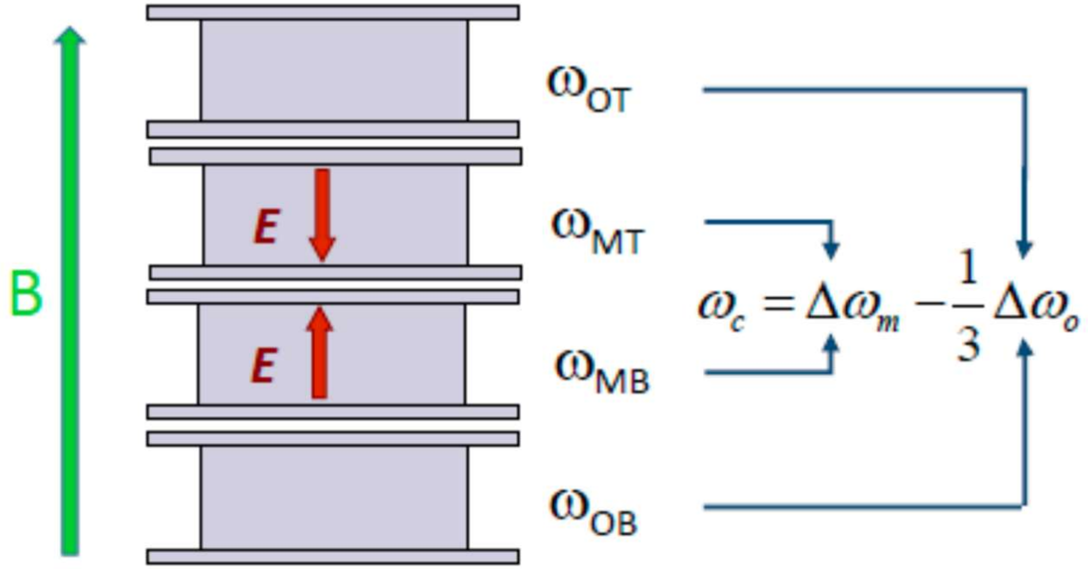


4 mercury vapor Cells:
2 with opposite E fields
2 for B field normalization

$$H = -(\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E})$$

$$\omega_c = \frac{\mu}{\hbar}\left(-\frac{8}{3}\frac{\partial^3 B}{\partial z^3}\Delta z^3\right) + \frac{4dE}{\hbar}$$

Cancels up to 2nd order gradient noise
Same EDM sensitivity as Middle Difference



Why Do We Need So Many Experiments?

Electron EDM

TVPV pseudoscalar-scalar eN coupling

TVPV tensor eN coupling

Short-distance contribution to d_n

Short distance contribution to d_p

TVPV isoscalar πN coupling

TVPV isovector πN coupling

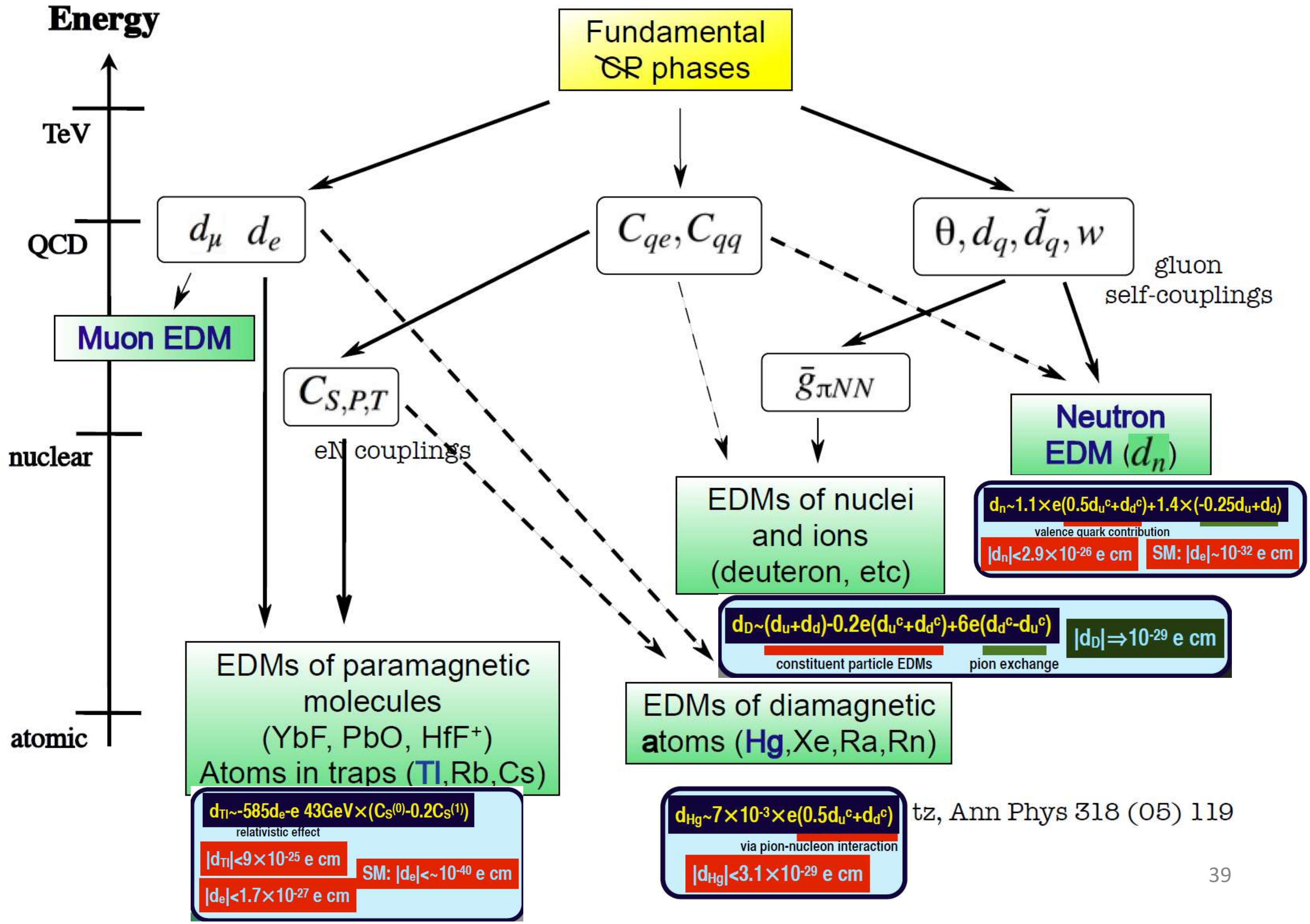
$$d = \underbrace{\alpha_{d_e} d_e + \alpha_{C_S} C_S}_{\text{Paramagnetic Systems}} + \underbrace{\alpha_{C_T} C_T + \alpha_{\bar{d}_n} \bar{d}_n + \alpha_{\bar{d}_p} \bar{d}_p + \alpha_{g_\pi^0} \bar{g}_\pi^0 + \alpha_{g_\pi^1} \bar{g}_\pi^1,}_{\text{Diamagnetic Systems}}$$

Paramagnetic Systems

Diamagnetic Systems

T. Chupp, M. Ramsey-Musolf, Phys. Rev. **C91** 035502 (2015)

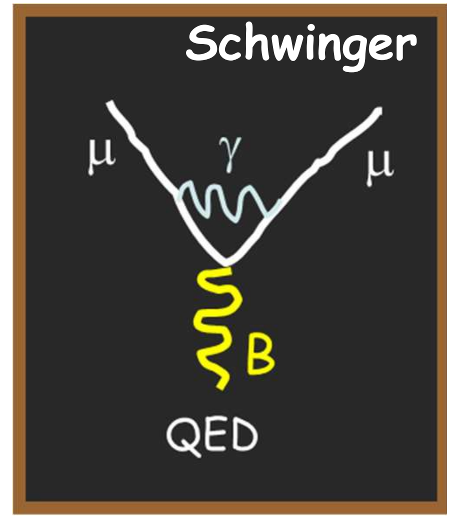
CP-violation in Low Energy Phenomena



In 1947, small deviations from g = 2 for the “pointlike” electron were observed at about the ~ 0.1% level

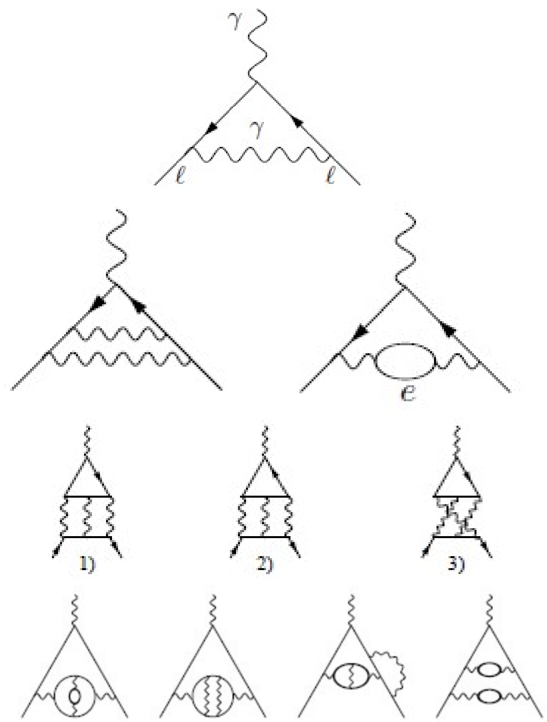
What is that ??

$$a_e = \frac{(g-2)}{2} \approx \frac{1}{2}\frac{\alpha}{\pi} \approx \frac{1}{800}$$



- Schwinger calculates 1st order radiative correction
- It agrees with experiment
- Higher-order terms are expansions in powers of α/π
- The set of radiative terms, represents the QED anomalous magnetic moment contribution for the leptons

$$a = \sum_{j=1} C_j \left(\frac{\alpha}{\pi}\right)^j$$



Another story, but a_e is calculated so precisely (and accurately) that we obtain the best α from it:

$$\frac{1}{\alpha}(a_e) = 137.035\,999\,085\,(12)(8x)(33)$$

See the article by Kinoshita in Lepton Dipole Moments

QED recent update, including tenth-order terms ! 12,672 diagrams

Complete Tenth-Order QED Contribution to the Muon $g-2$

Tatsumi Aoyama,[1,2] Masashi Hayakawa,[3,2] Toichiro Kinoshita,[4,2] and Makiko Nio[2]

[1] *Kobayashi-Maskawa Institute for the Origin of Particles and the Universe (KMI), Nagoya University, Nagoya, 464-8602, Japan*

[2] *Nishina Center, RIKEN, Wako, Japan 351-0198*

[3] *Department of Physics, Nagoya University, Nagoya, Japan 464-8602*

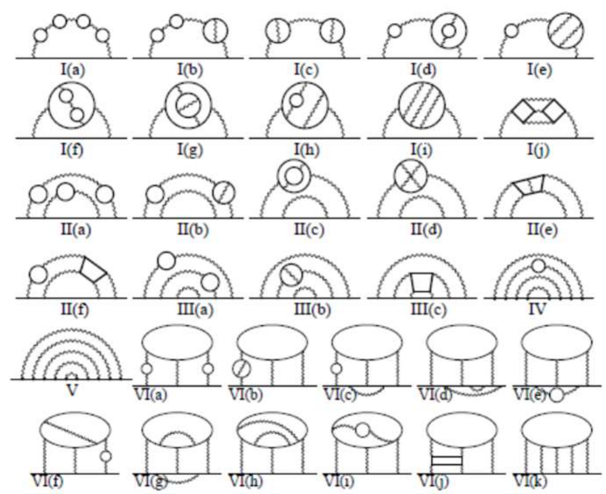
[4] *Laboratory for Elementary Particle Physics, Cornell University, Ithaca, New York, 14853, U.S.A*

(Dated: May 29, 2012)

$$a_\mu(QED)^* = 116\,584\,718.09(14)(4)_\alpha \times 10^{-11}$$

Note: way better than expt.

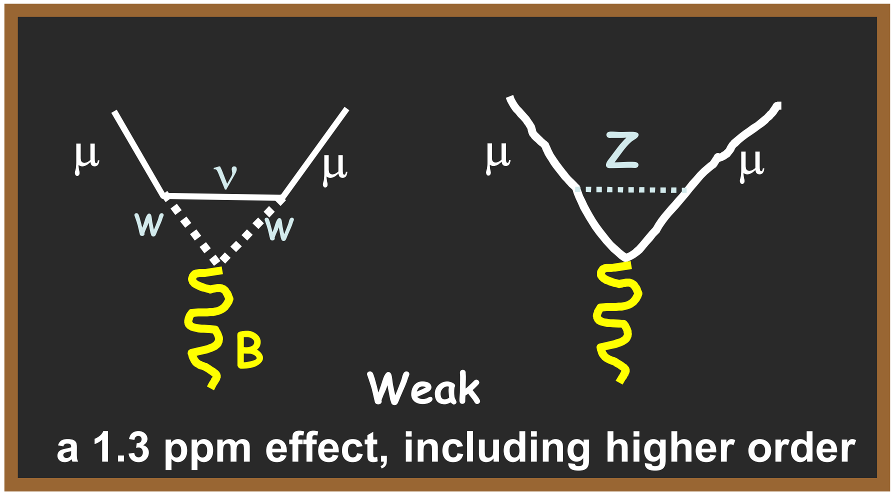
Do not try to calculate these at home:



arXiv:1205.5370v2 [hep-ph] 27 May 2012

* QED value here from 2010

The Electroweak theory says, e.g., we can replace any γ with a *Z* … and compute the Weak contribution to the anomaly

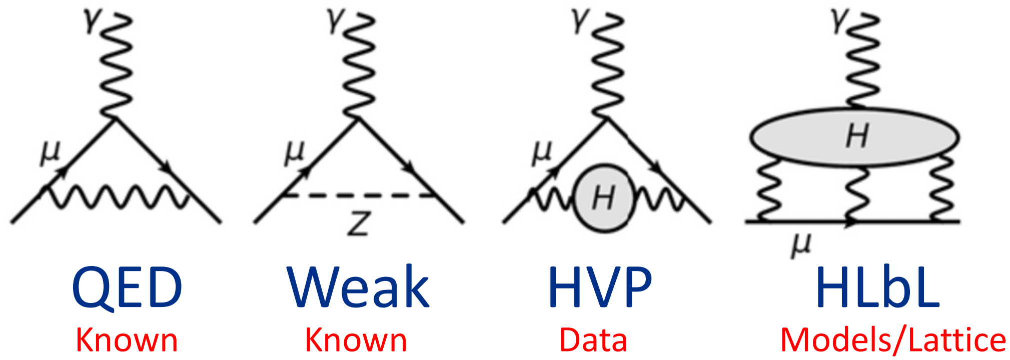


Known well, but wasn't easy

$$a_\mu(Weak) = 152(2)(1) \times 10^{-11}$$

Note: also way better than expt.

Standard Model contributions to a_μ … updates → 3.6 σ



	Value ($\times 10^{-10}$) units
QED ($\gamma + \ell$)	$11\,658\,471.8951 \pm 0.0009 \pm 0.0019 \pm 0.0007 \pm 0.0077_\alpha$
HVP(lo) Davier17	692.6 ± 3.33
HVP(lo)KNT2017	693.9 ± 2.6
HVP(ho) KNT2017	-9.84 ± 0.07
HLbL Glasgow	10.5 ± 2.6
EW	15.4 ± 0.1
Total SM Davier17	$11\,659\,181.7 \pm 4.2$
Total SM KNT17	$11\,659\,182.7 \pm 3.7$

This is a fancy guess; it will change

BNL E821 δa_μ(Expt) = ± 6.3

Spin motion for a particle *moving* in a magnetic field

$$\omega_S = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

$$\omega_C = \frac{eB}{mc\gamma}$$

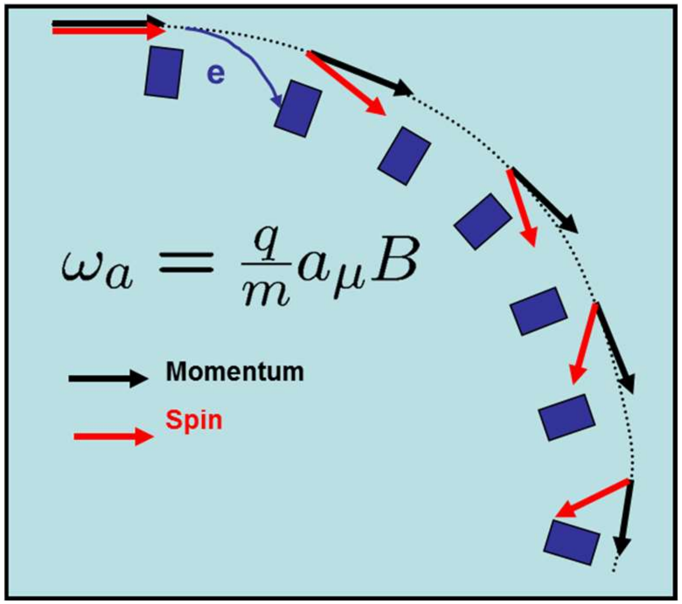
The **Spin** frequency relative to the **Cyclotron** frequency is the "anomalous precession frequency", ω_a

Does **NOT** depend on γ !

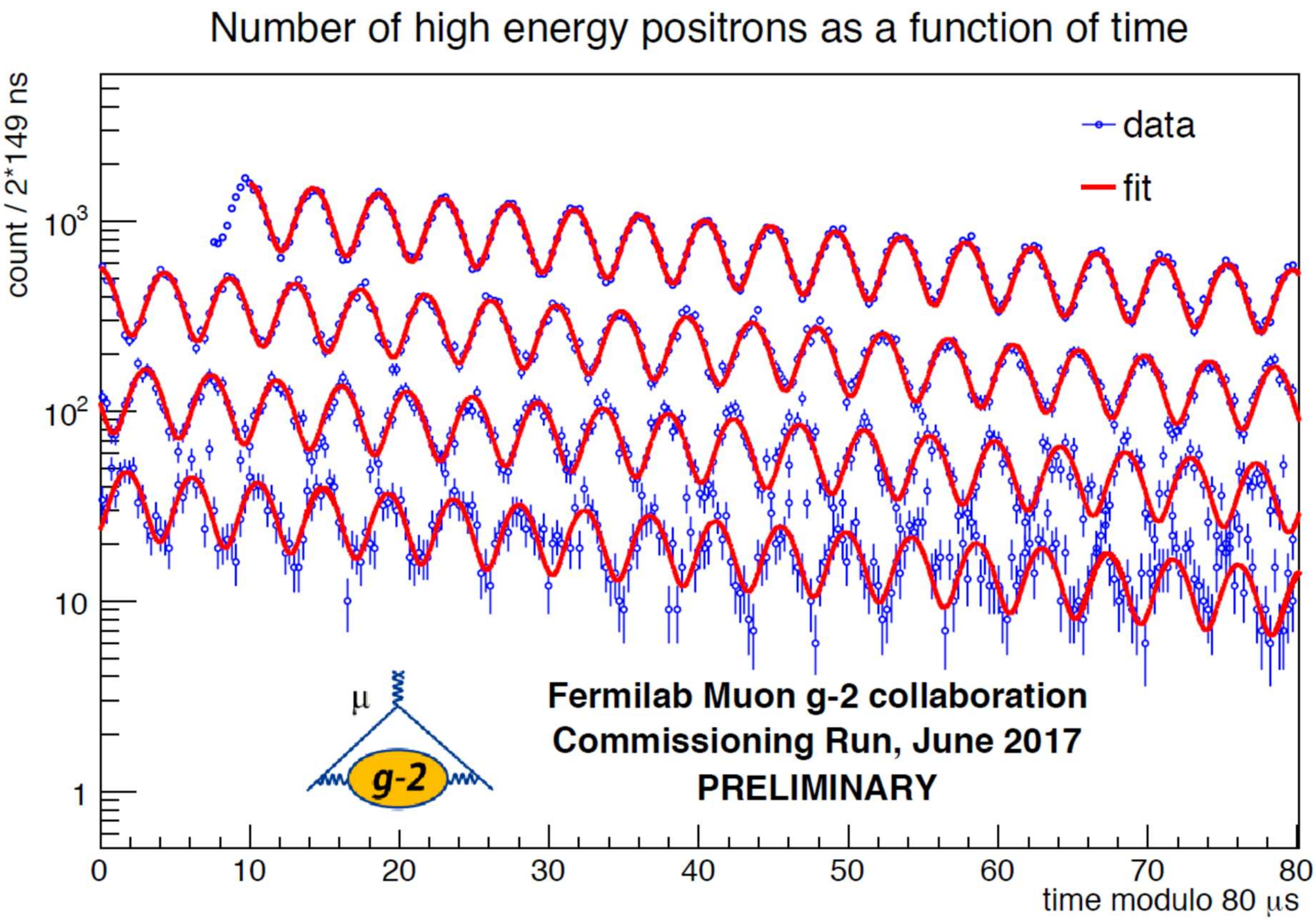
Proportional to g - 2 and ***B*** !

$$\omega_a = \omega_S - \omega_C$$

$$= \left(\frac{g-2}{2}\right)\frac{eB}{mc} = a\frac{eB}{mc}$$



Getting better … : June 25



Questions?