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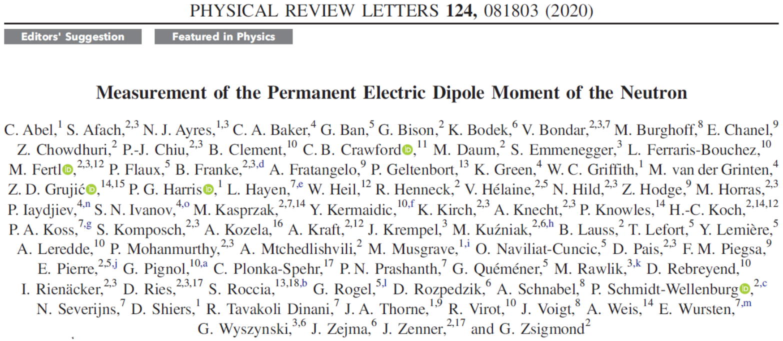
A New Limit on the Neutron Electric Dipole Moment

Pin-Jung Chiu
on behalf of the nEDM collaboration at PSI

EXA online conference
14 September 2021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Editors' Suggestion | Featured in Physics

Measurement of the Permanent Electric Dipole Moment of the Neutron

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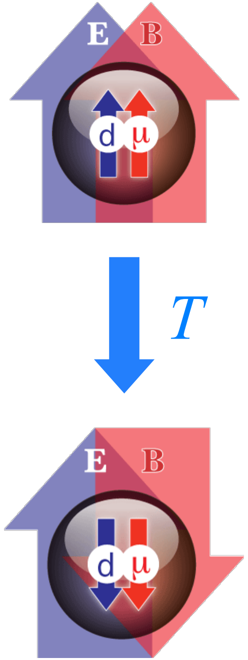
CP violation and electric dipole moment

- Baryon asymmetry of the Universe → CP violation
- Electric dipole moment (EDM): $\cancel{P}, \cancel{T} \rightarrow C\cancel{P}$

$$\begin{aligned}\mathcal{H} &= -\boldsymbol{d}\cdot\boldsymbol{E} - \boldsymbol{\mu}\cdot\boldsymbol{B} \\ &= -d\frac{\boldsymbol{\sigma}}{|\boldsymbol{\sigma}|}\cdot\boldsymbol{E} - \mu\frac{\boldsymbol{\sigma}}{|\boldsymbol{\sigma}|}\cdot\boldsymbol{B}\end{aligned}$$

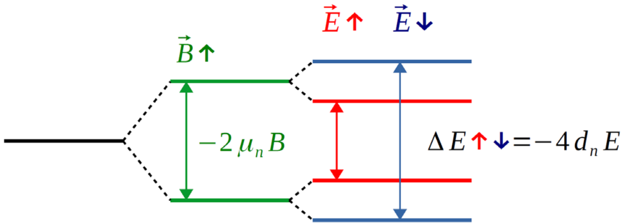
For spin-1/2 neutron: $\mathcal{H} = -2\left(d_{\mathrm{n}}\boldsymbol{E} + \mu_{\mathrm{n}}\boldsymbol{B}\right)\cdot\boldsymbol{\sigma}$

Time reversal: $\mathcal{H}_T = +2\left(+d_{\mathrm{n}}\boldsymbol{E} - \mu_{\mathrm{n}}\boldsymbol{B}\right)\cdot\boldsymbol{\sigma} \neq \mathcal{H}$



Measurement principle

- Energy splits $\mathcal{H} = -2\left(d_{\mathrm{n}}\boldsymbol{E} + \mu_{\mathrm{n}}\boldsymbol{B}\right)\cdot\boldsymbol{\sigma}$



- Measure the Larmor frequency of the neutron under parallel/antiparallel ***E*** and ***B***

$$hf_{\mathrm{n}}^{\uparrow\uparrow} = -2d_{\mathrm{n}}E^{\uparrow\uparrow} - 2\mu_{\mathrm{n}}B^{\uparrow\uparrow}$$

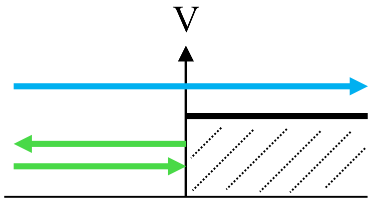
$$hf_{\mathrm{n}}^{\uparrow\downarrow} = +2d_{\mathrm{n}}E^{\uparrow\downarrow} - 2\mu_{\mathrm{n}}B^{\uparrow\downarrow}$$

$$\Rightarrow d_{\mathrm{n}} = \frac{h\left(f_{\mathrm{n}}^{\uparrow\uparrow} - f_{\mathrm{n}}^{\uparrow\downarrow}\right) - 2\mu_{\mathrm{n}}\left(\boxed{-B^{\uparrow\uparrow} + B^{\uparrow\downarrow}}\right)}{-2\left(E^{\uparrow\uparrow} + E^{\uparrow\downarrow}\right)}.$$

Stability and uniformity! → Magnetometers

Ultracold neutron (UCN)

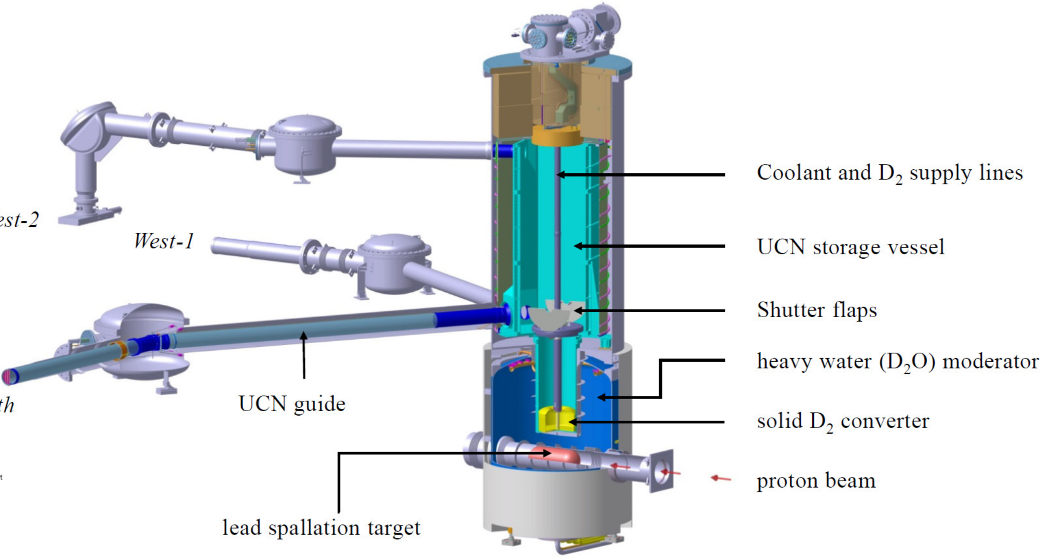
- UCN properties
  - kinetic energy ≤ 300 neV
  - temperature: 3-5 mK
  - velocity ≤ 8 m/s
  - storable



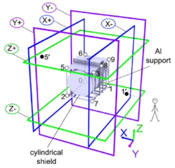
Optical potential (Fermi potential)

$V_F \leq 180 - 300$ neV

(e.g., Ni, Be, BeO, DLC)

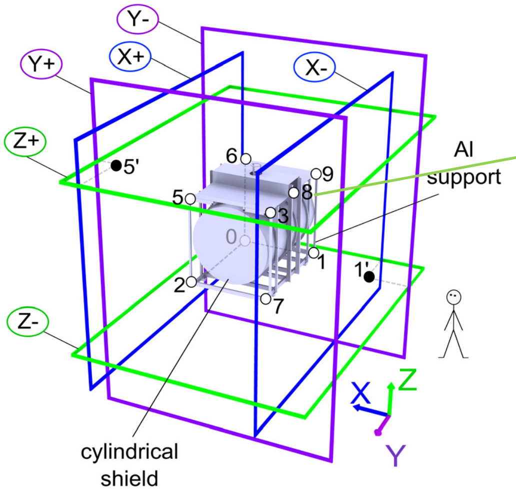


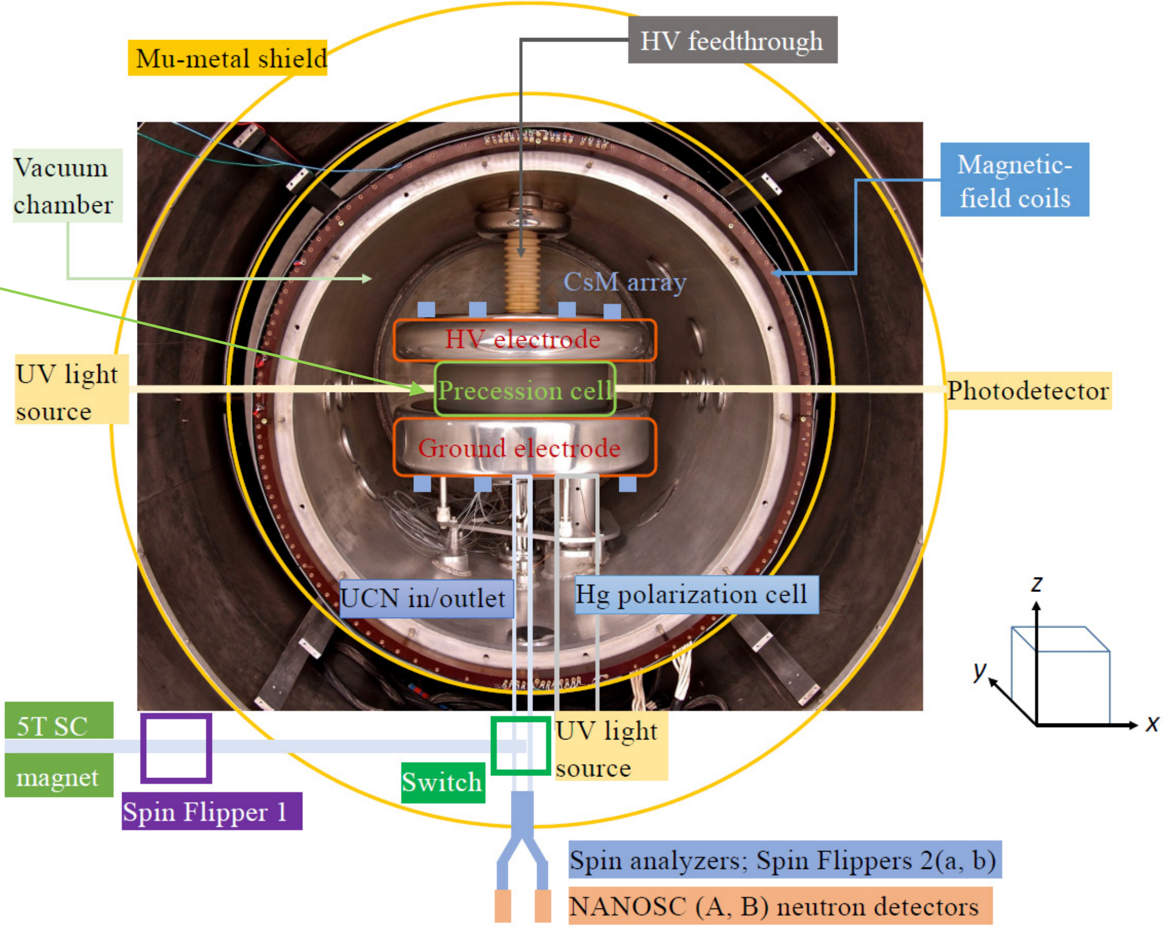
nEDM



Apparatus

Polarized UCN and ^{199}Hg atoms

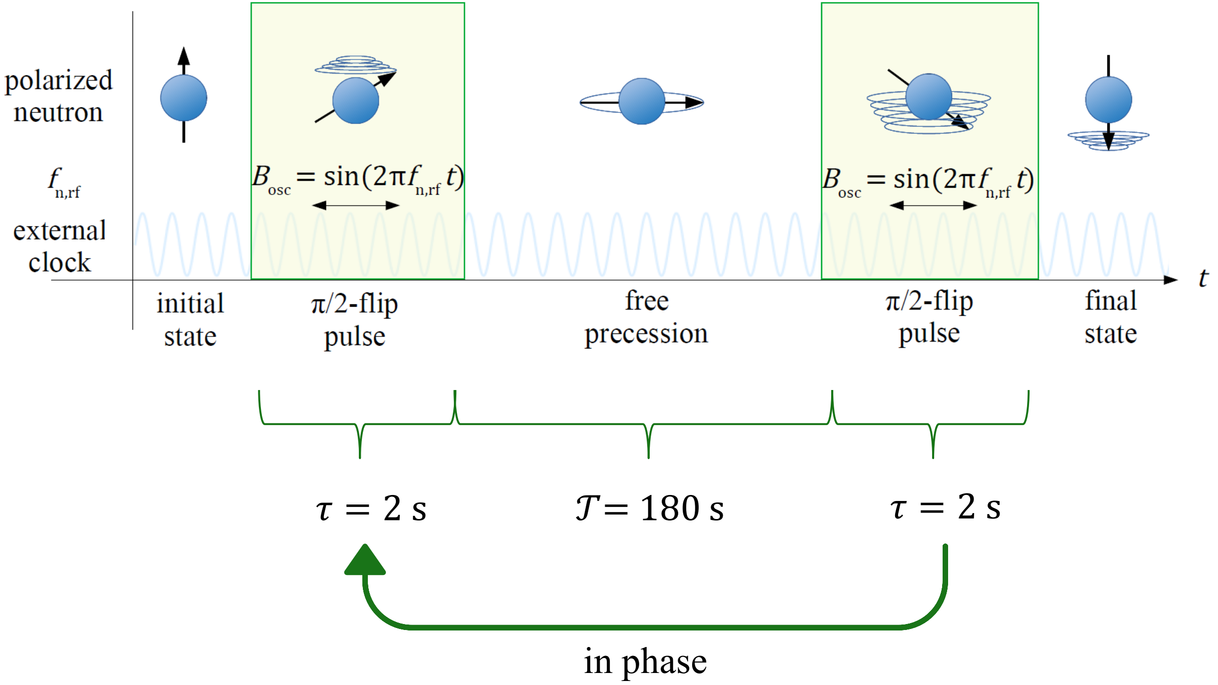




Ref.: S. Afach *et al.*, J. Appl. Phys. 116, 084510 (2014).

Ramsey’s method of separated oscillatory fields

one measurement “cycle”



polarized neutron

$f_{\mathrm{n,rf}}$

external clock

$B_{\mathrm{osc}} = \sin(2\pi f_{\mathrm{n,rf}}\, t)$

$B_{\mathrm{osc}} = \sin(2\pi f_{\mathrm{n,rf}}\, t)$

t

initial state

π/2-flip pulse

free precession

π/2-flip pulse

final state

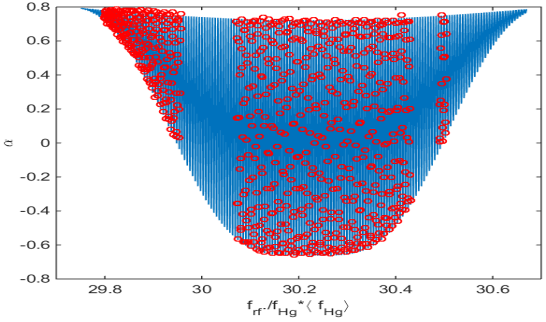
$\tau = 2\ \mathrm{s}$

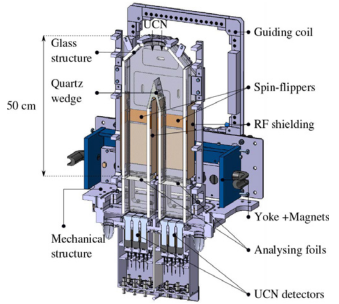
$\mathcal{T} = 180\ \mathrm{s}$

$\tau = 2\ \mathrm{s}$

in phase

Ramsey’s pattern





Refs.: N. F. Ramsey, Phys. Rev. 78, 695 (1950),
S. Afach *et al.*, Eur. Phys. J. A 51, 143 (2015).

Asymmetry: $\mathcal{A} = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$

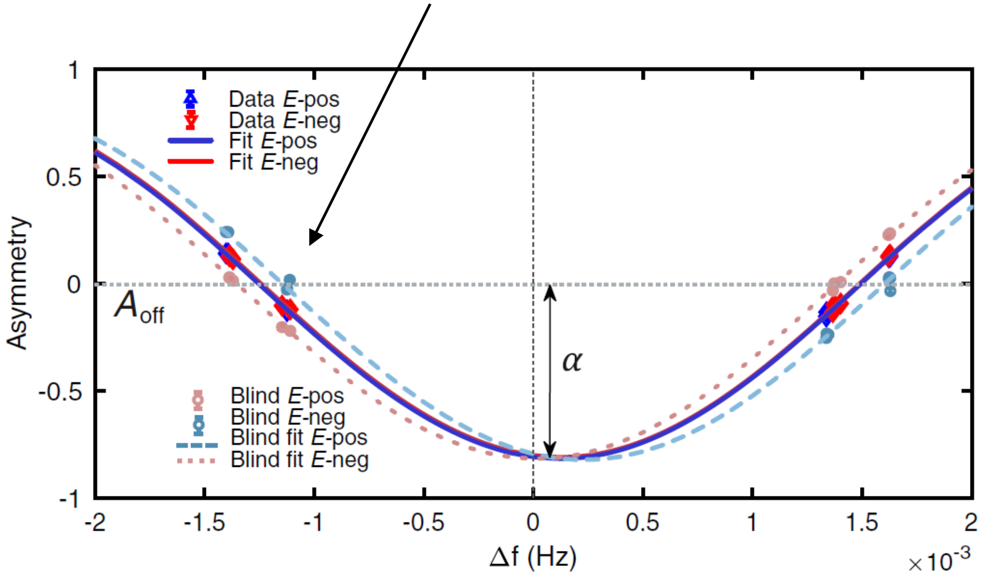
Ramsey central fringe

$$\mathcal{A}_i = \mathcal{A}_{\text{off}} \mp \alpha \cos\left(\frac{\pi\Delta f_i}{\Delta\upsilon} + \phi\right)$$

Δf_i: spin-flip frequency
$\Delta\upsilon = (2T + 8\tau/\pi)^{-1} = 2.7$ mHz

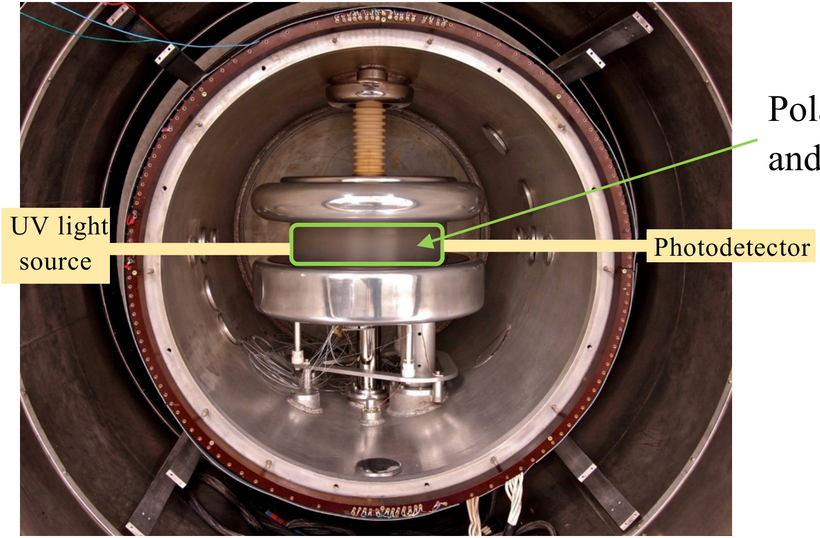
Free parameters to be fitted:
$\mathcal{A}_{\text{off}}$: offset
α: visibility
ϕ: phase

Spin-flip pulses were alternated between four frequencies at the “working points”



^{199}Hg comagnetometer (HgM)

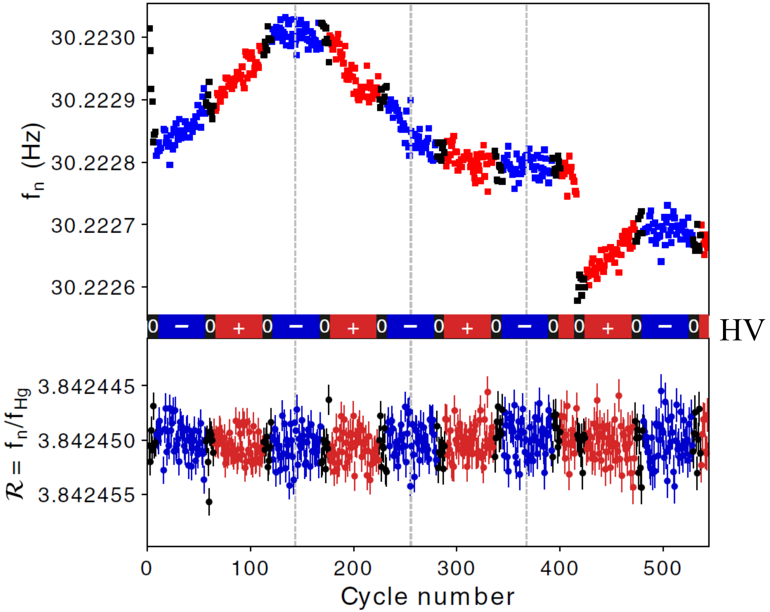
- Use ^{199}Hg atoms to correct for 1st-order magnetic-field drifts/noise
- $\mathcal{R} = \frac{f_\mathrm{n}}{f_\mathrm{Hg}}$



UV light source

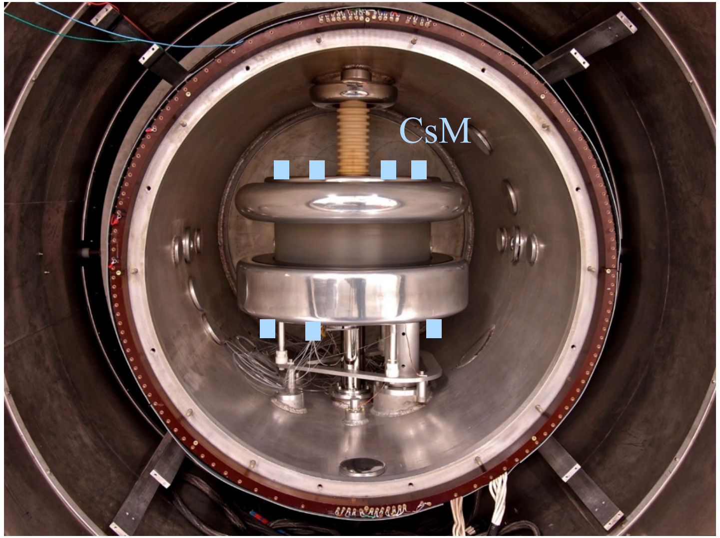
Photodetector

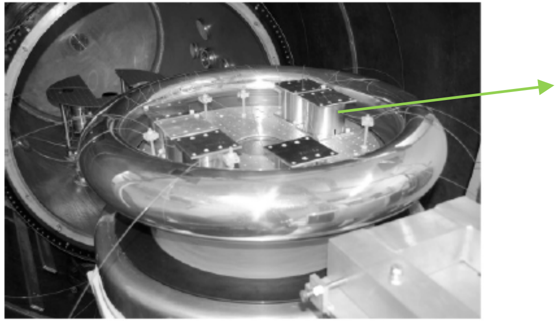
Polarized UCN and ^{199}Hg atoms



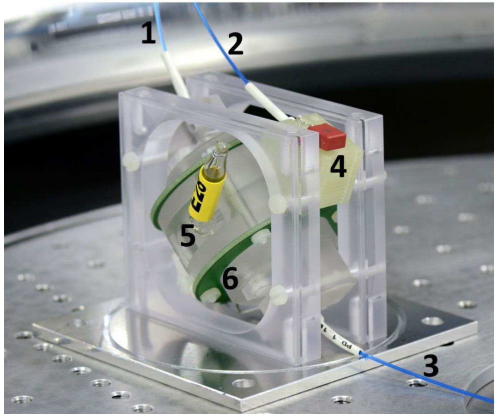
^{133}Cs magnetometers (CsM)

- 16 optically-pumped Cs-vapor magnetometers
- Installed on three layers above and below the precession chamber





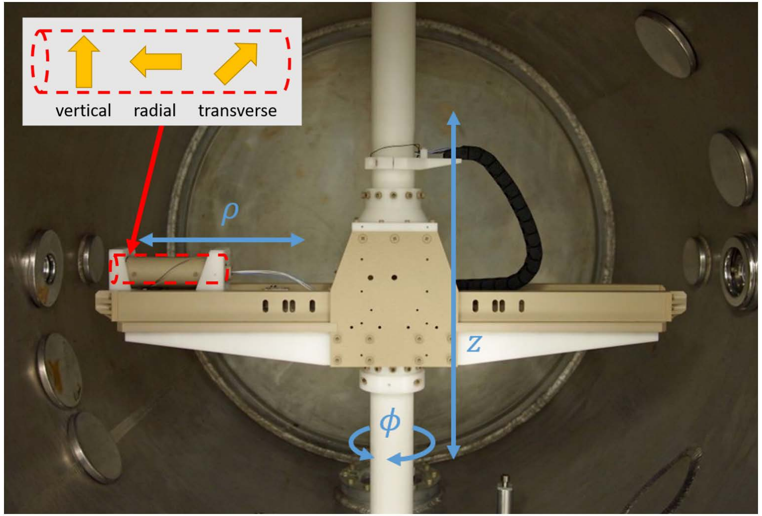
6 optically coupled CsM
on the HV electrode



Ref.: C. Abel *et al.*, Phys. Rev. A 101, 053419 (2020).

Magnetic-field mapping

- 3-axis fluxgate magnetometer (r, φ, z)
- Measure fields at thousands of points
- Decompose field into a basis consisting of 63 modes
- Corrects for:
  - Transverse-field shift
  - Higher-order fields in d^{false}



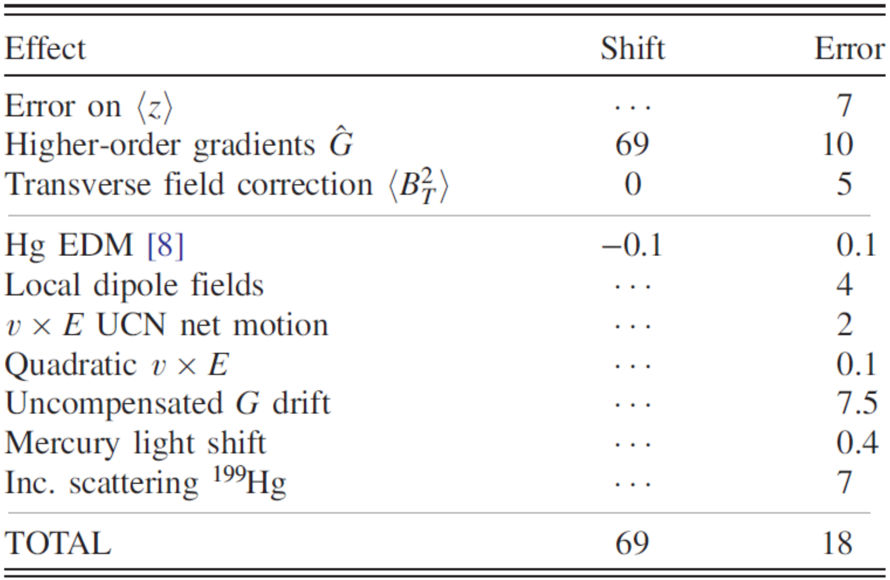
Ref.: C. Abel *et al.*, arXiv:2103.09039 [physics.ins-det] (2021).

Systematic effects

Cancelled in perfectly uniform and stable ***B***

- $$\mathcal{R} = \frac{f_{\mathrm{n}}}{f_{\mathrm{Hg}}} = \left|\frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\right|\left(1 \overbrace{+ \delta_{\mathrm{EDM}} + \delta_{\mathrm{EDM}}^{\mathrm{false}} + \delta_{\mathrm{quad}}}^{\boldsymbol{E}} \overbrace{+ \delta_{\mathrm{grav}} + \delta_{\mathrm{T}}}^{\boldsymbol{B}} \overbrace{+ \delta_{\mathrm{Earth}} + \delta_{\mathrm{light}} + \delta_{\mathrm{inc}} + \delta_{\mathrm{other}}}^{\text{secondary effects}}\right)$$

$10^{-28} e \cdot \mathrm{cm}$



Effect	Shift	Error
Error on $\langle z \rangle$	⋯	7
Higher-order gradients $\hat{G}$	69	10
Transverse field correction $\langle B_T^2 \rangle$	0	5
Hg EDM [8]	−0.1	0.1
Local dipole fields	⋯	4
$v \times E$ UCN net motion	⋯	2
Quadratic $v \times E$	⋯	0.1
Uncompensated G drift	⋯	7.5
Mercury light shift	⋯	0.4
Inc. scattering ^{199}Hg	⋯	7
TOTAL	69	18

magnetic-field maps

→ measurements at PTB Berlin

→ CsM

→ not anticipated earlier

- Total systematic error $0.18 \times 10^{-26} e \cdot \mathrm{cm}$
- 5 times improvement from the previous result
- 1/5 of the statistical error

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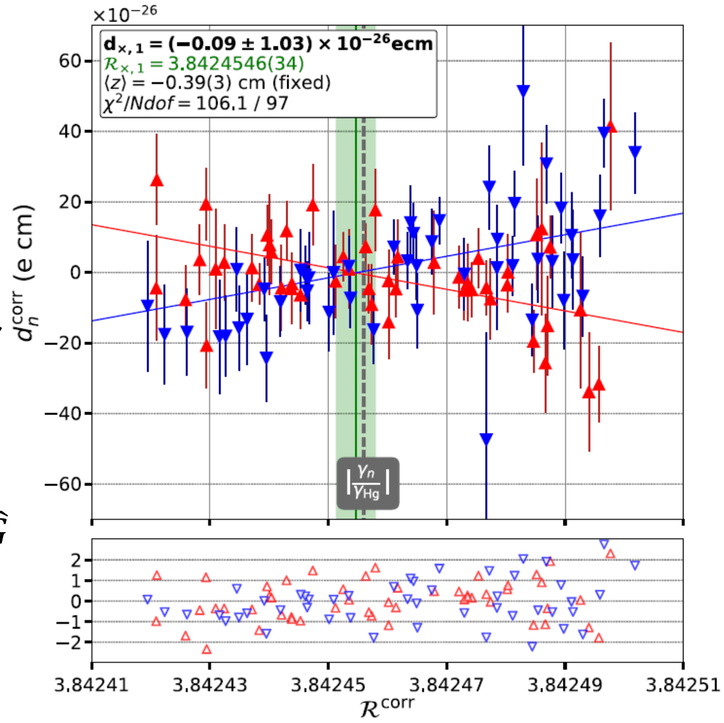
Crossing-point analysis

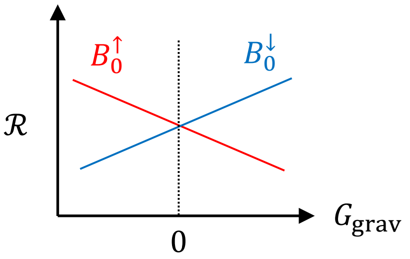
- $d_{\mathrm{n}} = \frac{h\langle f_{\mathrm{Hg}}\rangle}{-4E}\left(R^{\uparrow\uparrow} - R^{\uparrow\downarrow}\right)$

field maps

- $d^{\mathrm{meas}} = d^{\mathrm{corr}} + \frac{\hbar}{8c^2}\left|\gamma_{\mathrm{n}}\,\gamma_{\mathrm{Hg}}\right|\mathcal{R}^2\left(\hat{G} + G_{\mathrm{grav}}\right)$



$$d_{\mathrm{n}}^{\mathrm{corr}} = d_{\mathrm{n}}^{\mathrm{meas}} - \frac{\hbar}{8c^2}\left|\gamma_{\mathrm{n}}\,\gamma_{\mathrm{Hg}}\right|\mathcal{R}^2\hat{G}$$

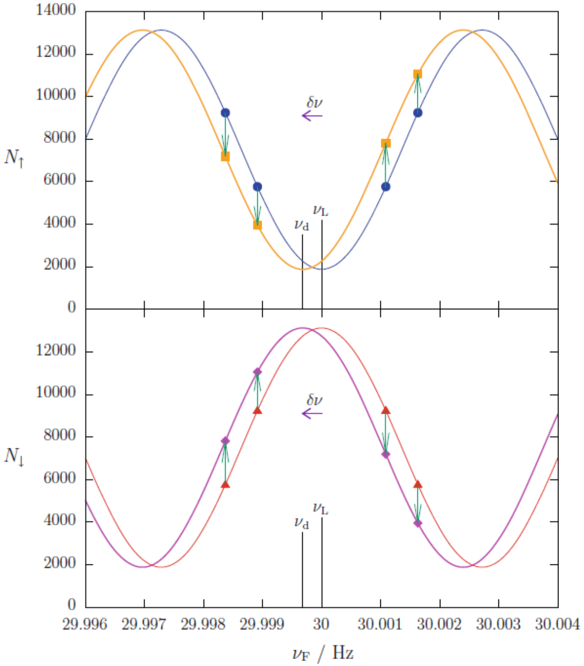


At the crossing point $G_{\mathrm{grav}} = 0$ ⟶ $\mathcal{R}^{\mathrm{corr}} = \mathcal{R}/(1 + \delta_{\mathrm{T}} + \delta_{\mathrm{Earth}})$

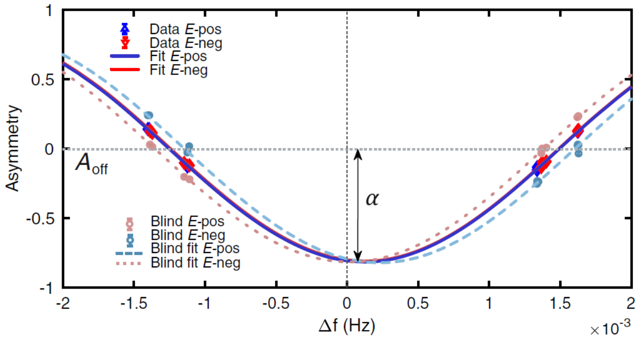
field maps

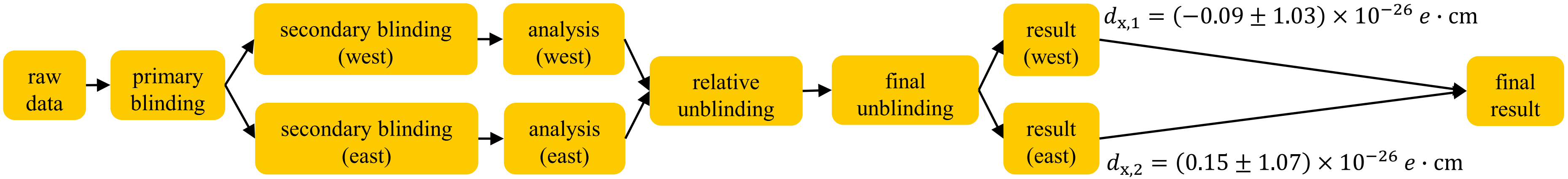
Blinding and analysis strategy

Ref.: N. J. Ayres *et al.*, Eur. Phys. J. A 57, 152 (2021).



- Add an $\boldsymbol{E}$ dependent shift to f_n by moving counts between two detectors





raw data → primary blinding → secondary blinding (west) → analysis (west) → relative unblinding

primary blinding → secondary blinding (east) → analysis (east) → relative unblinding

relative unblinding → final unblinding → result (west) / result (east) → final result

$d_{x,1} = (-0.09 \pm 1.03) \times 10^{-26}\ e \cdot \mathrm{cm}$

$d_{x,2} = (0.15 \pm 1.07) \times 10^{-26}\ e \cdot \mathrm{cm}$

New result

- Previous result

Ref.: J. M. Pendlebury *et al.*, Phys. Rev. D 92, 092003 (2015).

$$d_\mathrm{n} = \left(-0.2 \pm 1.5_\mathrm{stat} \pm 1.0_\mathrm{sys}\right) \times 10^{-26}\ e \cdot \mathrm{cm} \rightarrow |d_\mathrm{n}| < 3 \times 10^{-26}\ e \cdot \mathrm{cm}\ (90\%\ \mathrm{C.L.})$$

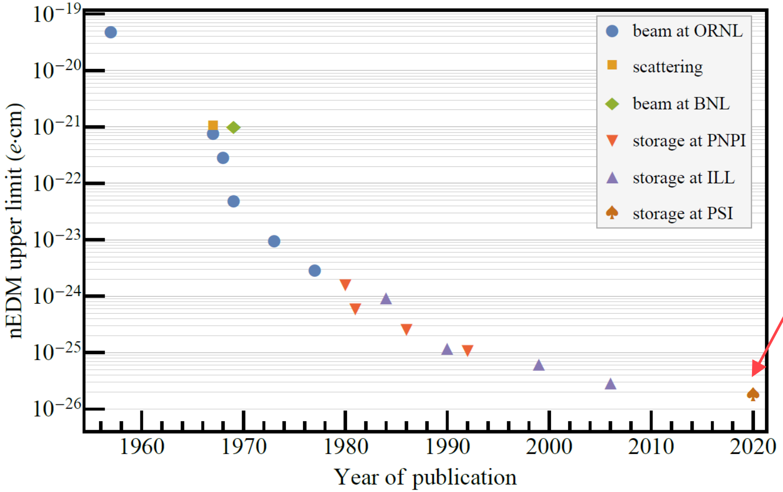
× 5

- New result

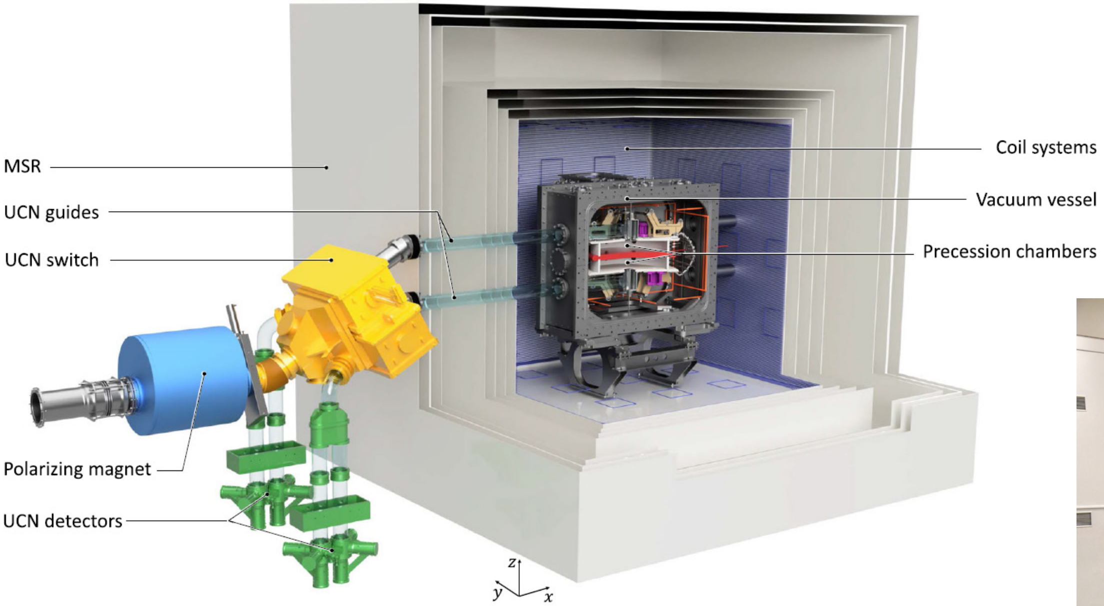
Ref.: C. Abel *et al.*, Phys. Rev. Lett. 124, 081803 (2020).

$$d_\mathrm{n} = \left(0.0 \pm 1.1_\mathrm{stat} \pm 0.2_\mathrm{sys}\right) \times 10^{-26}\ e \cdot \mathrm{cm} \rightarrow |d_\mathrm{n}| < 1.8 \times 10^{-26}\ e \cdot \mathrm{cm}\ (90\%\ \mathrm{C.L.})$$

1/5



n2EDM coming soon!



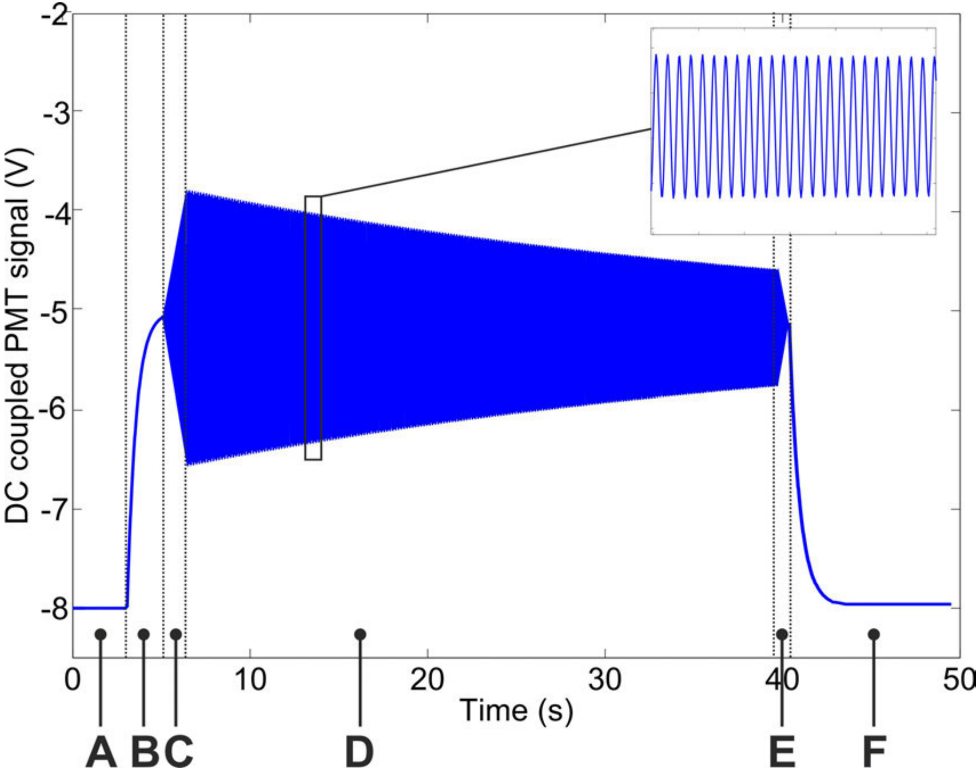
- A new double-chamber apparatus
- Sensitivity goal: $d_{\mathrm{n}} \sim 10^{-27}\ e \cdot \mathrm{cm}$

Collaboration meeting, November 2019, Mainz TRIGA Reactor

Thank you very much~

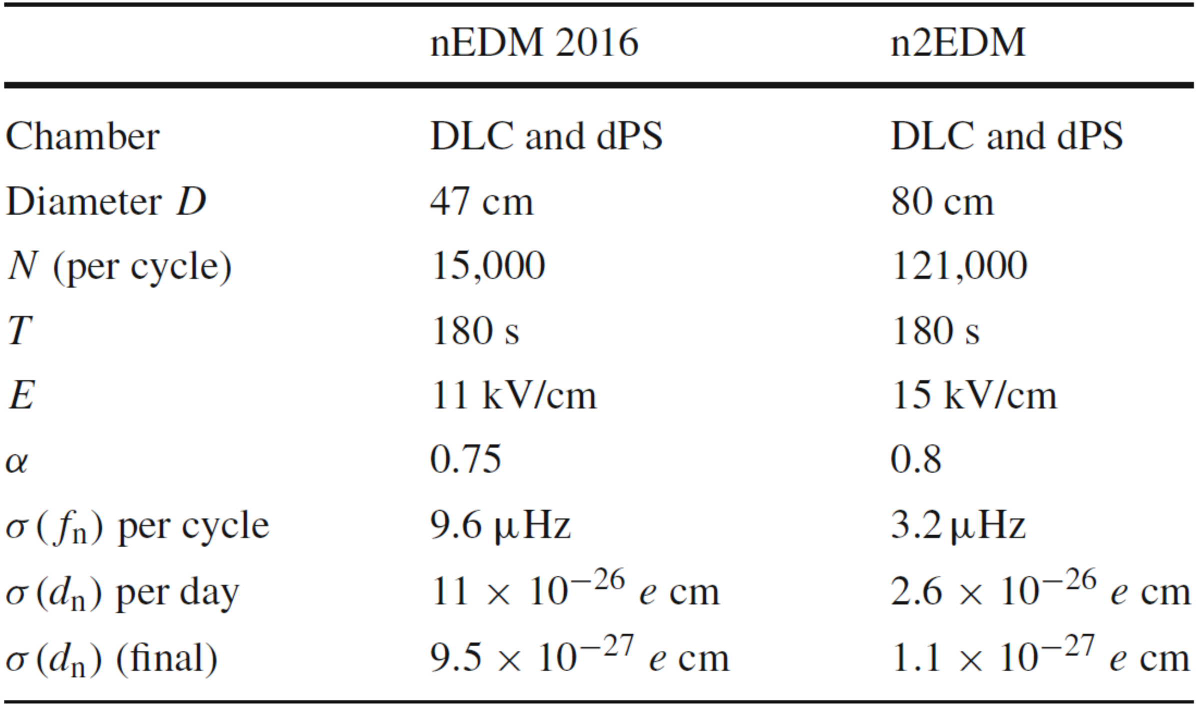
Hg free-induction-decay signal

- Pure Hg measurement



Ref.: S. Komposch, PhD thesis (2017).

nEDM vs. n2EDM

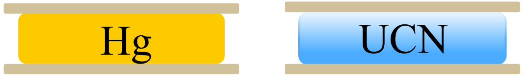


	nEDM 2016	n2EDM
Chamber	DLC and dPS	DLC and dPS
Diameter D	47 cm	80 cm
N (per cycle)	15,000	121,000
T	180 s	180 s
E	11 kV/cm	15 kV/cm
α	0.75	0.8
$\sigma(f_n)$ per cycle	9.6 μHz	3.2 μHz
$\sigma(d_n)$ per day	$11 \times 10^{-26}\ e$ cm	$2.6 \times 10^{-26}\ e$ cm
$\sigma(d_n)$ (final)	$9.5 \times 10^{-27}\ e$ cm	$1.1 \times 10^{-27}\ e$ cm

Ref.: N. J. Ayres *et al.*, Eur. Phys. J. C 81, 512 (2021).

Systematic effects --- *B* terms

- $\mathcal{R} = \frac{f_\mathrm{n}}{f_\mathrm{Hg}} = \left|\frac{\gamma_\mathrm{n}}{\gamma_\mathrm{Hg}}\right|\left(1 + \underbrace{\delta_\mathrm{EDM} + \delta_\mathrm{EDM}^\mathrm{false} + \delta_\mathrm{quad}}_{\boldsymbol{E}} + \underbrace{\delta_\mathrm{grav} + \delta_\mathrm{T}}_{\boldsymbol{B}} + \underbrace{\delta_\mathrm{Earth} + \delta_\mathrm{light} + \delta_\mathrm{inc} + \delta_\mathrm{other}}_{\text{secondary effects}}\right)$



$\frac{\gamma_\mathrm{Hg}}{2\pi} \approx 8\mathrm{Hz}/\mu\mathrm{T}$

$\bar{v}_\mathrm{Hg} \approx 170\ \mathrm{m/s}$

$\frac{\gamma_\mathrm{n}}{2\pi} \approx 30\mathrm{Hz}/\mu\mathrm{T}$

$\bar{v}_\mathrm{n} \approx 4\ \mathrm{m/s}$

Gravitational shift

$$\delta_\mathrm{grav} = \frac{\langle z \rangle}{|B_0|} G_\mathrm{grav}$$

Center-of-mass offset of UCN
$\langle z \rangle = -0.39(3)$ cm

Deduced from an auxiliary analysis
from the slope of $\partial\mathcal{R}/\partial G_\mathrm{grav}$

→ CsM + offline field maps

Transverse-field shift

$$\delta_\mathrm{T} = \frac{\langle B_\mathrm{T}^2 \rangle}{2{B_0}^2} \qquad \langle B_\mathrm{T}^2 \rangle = \left\langle (B_\mathrm{x} - \langle B_\mathrm{x} \rangle)^2 + \left(B_\mathrm{y} - \langle B_\mathrm{y} \rangle\right)^2 \right\rangle$$

$\langle B_\mathrm{n} \rangle \neq \langle B_\mathrm{Hg} \rangle$

→ offline field maps

Systematic effects --- *E* terms

- $\mathcal{R} = \frac{f_{\mathrm{n}}}{f_{\mathrm{Hg}}} = \left|\frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\right| (1 + \underbrace{\delta_{\mathrm{EDM}} + \delta_{\mathrm{EDM}}^{\mathrm{false}} + \delta_{\mathrm{quad}}}_{\boldsymbol{E}} + \underbrace{\delta_{\mathrm{grav}} + \delta_{\mathrm{T}}}_{\boldsymbol{B}} + \underbrace{\delta_{\mathrm{Earth}} + \delta_{\mathrm{light}} + \delta_{\mathrm{inc}} + \delta_{\mathrm{other}}}_{\text{secondary effects}})$

True EDM term

- n EDM
- Hg EDM

$$\delta_{\mathrm{EDM}} = -\frac{2E}{\hbar|\gamma_{\mathrm{n}}|B_0}\left(d_{\mathrm{n}} + d_{\mathrm{n}\leftarrow\mathrm{Hg}}\right)$$

False EDM term

- relativistic motional field
  $\vec{B}_{\mathrm{m}} = \vec{E} \times \vec{v}/c^2$
- magnetic-field gradient

$$\delta_{\mathrm{EDM}}^{\mathrm{false}} = -\frac{2E}{\hbar|\gamma_{\mathrm{n}}|B_0}\left(d_{\mathrm{n}}^{\mathrm{net}} + d^{\mathrm{false}}\right)$$

$d_{\mathrm{n}}^{\mathrm{net}}$: net motion of UCN
d^{false}: random motions of UCN and Hg atoms
in a nonuniform ***B***

Quadratic in E term

- random motion of UCN and Hg
- consider only dominant shift on f_{Hg}

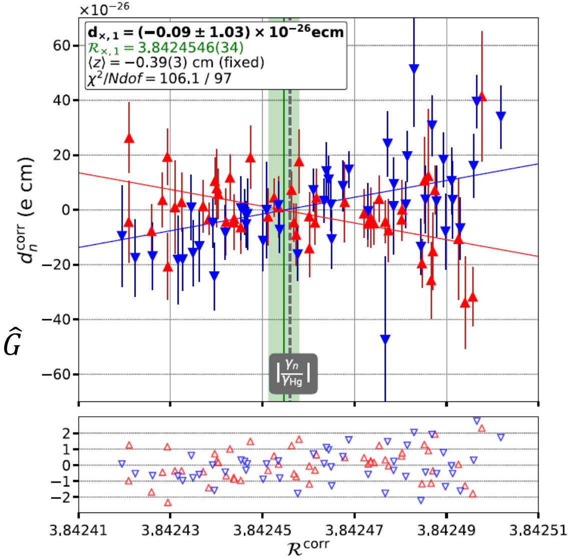
$$\delta_{\mathrm{quad}} = {\gamma_{\mathrm{Hg}}}^2 R^2 E^2/(4c^2)$$

Dominant systematic effects $\delta_{\mathrm{EDM}}^{\mathrm{false}} = -\frac{2E}{\hbar|\gamma_{\mathrm{n}}|B_0}\left(d_{\mathrm{n}}^{\mathrm{net}} + d^{\mathrm{false}}\right)$

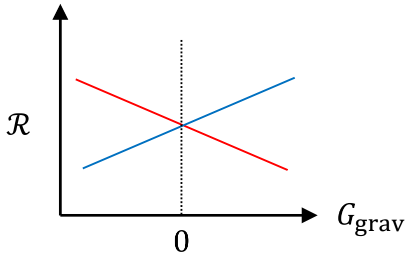
- $d^{\mathrm{false}} = \frac{\hbar}{8c^2}|\gamma_{\mathrm{n}}\,\gamma_{\mathrm{Hg}}|\mathcal{R}^2\left(\hat{G} + G_{\mathrm{grav}}\right)$

offline field maps

crossing-point analysis



$$d_{\mathrm{n}}^{\mathrm{corr}} = d_{\mathrm{n}}^{\mathrm{meas}} - \frac{\hbar}{8c^2}|\gamma_{\mathrm{n}}\,\gamma_{\mathrm{Hg}}|\mathcal{R}^2\hat{G}$$



At the crossing point $G_{\mathrm{grav}} = 0 \longrightarrow \mathcal{R}^{\mathrm{corr}} = \mathcal{R}/(1 + \delta_{\mathrm{T}} + \delta_{\mathrm{Earth}})$

- $d_{\mathrm{n}}^{\mathrm{net}} = \eta\epsilon\,\cdot 6.7 \times 10^{-23} e \cdot \mathrm{cm/(m/s)}$

η: mean net velocity
ϵ: misalignment angle