Electric Dipole Moments

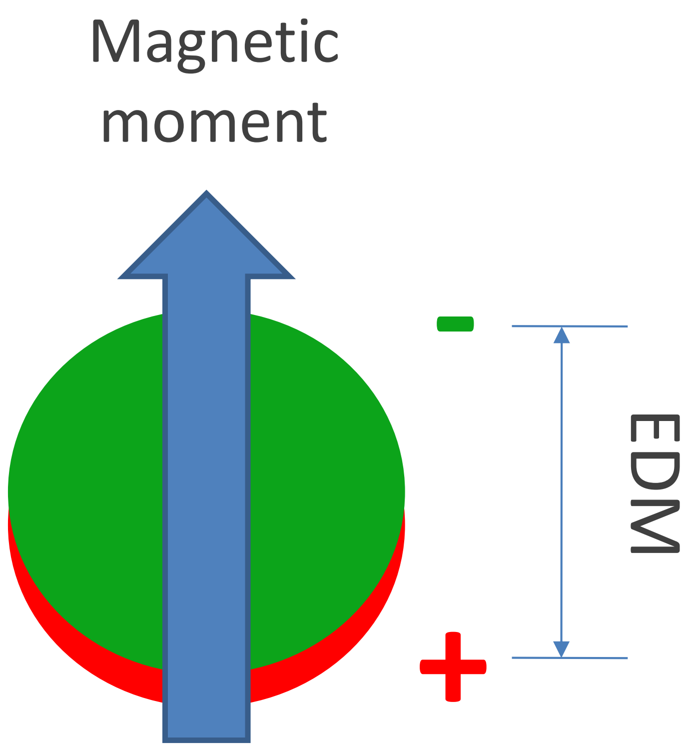
Peter Fierlinger
Technical University of Munich

30th Anniversary of the Rencontres du Vietnam
August 6-12, 2023
ICISE, Quy Nhon, Vietnam

Content

- EDMs and new physics
- Basic method
- Selected experiments
- New directions

Electric Dipole Moments

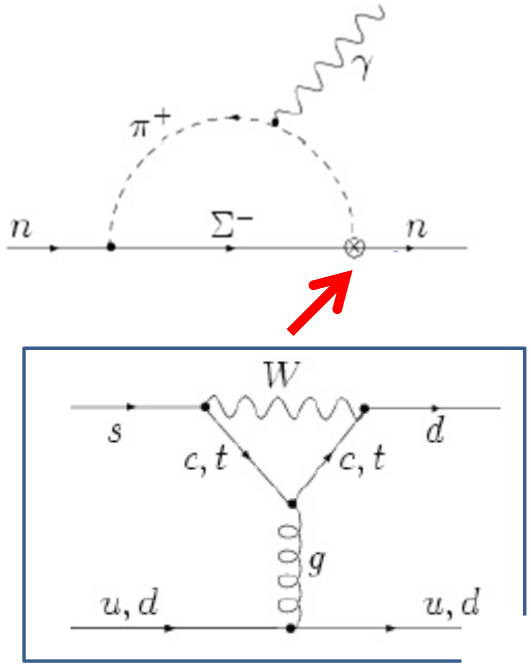


$$H = -\mu \mathbf{B} \cdot \frac{\mathbf{S}}{S} - d\mathbf{E} \cdot \frac{\mathbf{S}}{S}$$

- A „*fundamental*“ electric dipole moment (EDM) violates P and T symmetry *Purcell and Ramsey, PR78(1950)807*
- No classical EDM, rather a formfactor
- Also point-like particles have an EDM
- Upper limits are among the most precisely measured quantities: $d_n < 1.8 \cdot 10^{-26}$ ecm
- Current limits far away from Standard Model predictions
- A ‘model killer‘

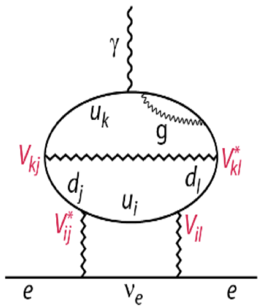
EDMs & Standard Model

CP violation from CKM



Neutron EDM $d_n \approx 10^{-32}$ ecm

Side note: $d_{electron} < 10^{-38}$ ecm…



Strong Interaction

CP-odd term in Lagrangian:

$$L_\theta = \bar{\theta}\,\frac{\alpha_s}{8\pi}\,G\tilde{G}$$

$$d_n(\bar{\theta}) \sim \bar{\theta}\,\frac{e}{m_n}\,\frac{m_*}{\Lambda_{QCD}} \sim 6.10^{-17}\,\bar{\theta}\,e\cdot cm$$

$$\bar{\theta} < 10^{-10}$$

Strong CP problem, Axions

details:

Rev. Mod. Phys. ***91****, 015001 (2019)*
Phys. Rev. C ***91****, 035502 (2015)*
Prog. Part. Nucl. Phys. ***71****, 21 (2013)*

Atomic and Molecular EDMs

Schiff moment:

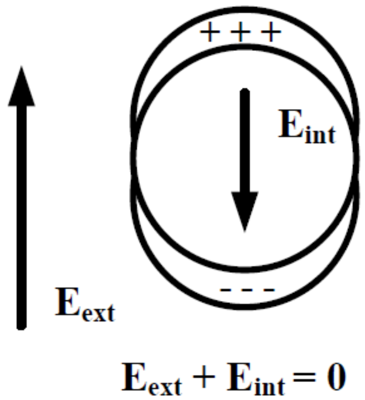
Non-perfect cancellation of E_{ext} in atomic shell

- Paramagnetic atoms: relativistic effects in electronic shell

$$d_a \propto d_e Z^3$$ Sandars, 1968

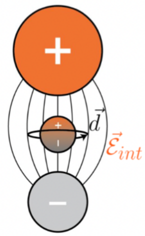
- Diamagnetic atoms: finite size of nucleus counteracts field cancelation

$$d_a \propto d_{nucl} Z^2$$ Schiff 1963; Sandars, 1968; Feinberg 1977; ... - 2010

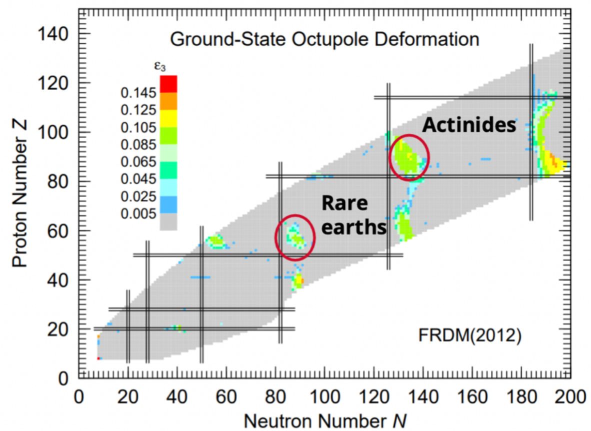


Many possibilities for further EDM enhancements:

- Deformed nuclei (Ra, Rn, also Fr, Ac, Pa)
- Large electric fields of polar molecules (YbF, ThO, BaF, TlF, SrF...) and molecular ions (HfF+,...), multi-atom polar molecules



L. P. Gaffney *et al.*, Nature 497, 199 (2013)



EDMs and new Physics

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

Dim. 6:

$$d_n \propto \frac{m_q}{\Lambda^2} \cdot e \cdot \phi_{\text{CPV}}$$

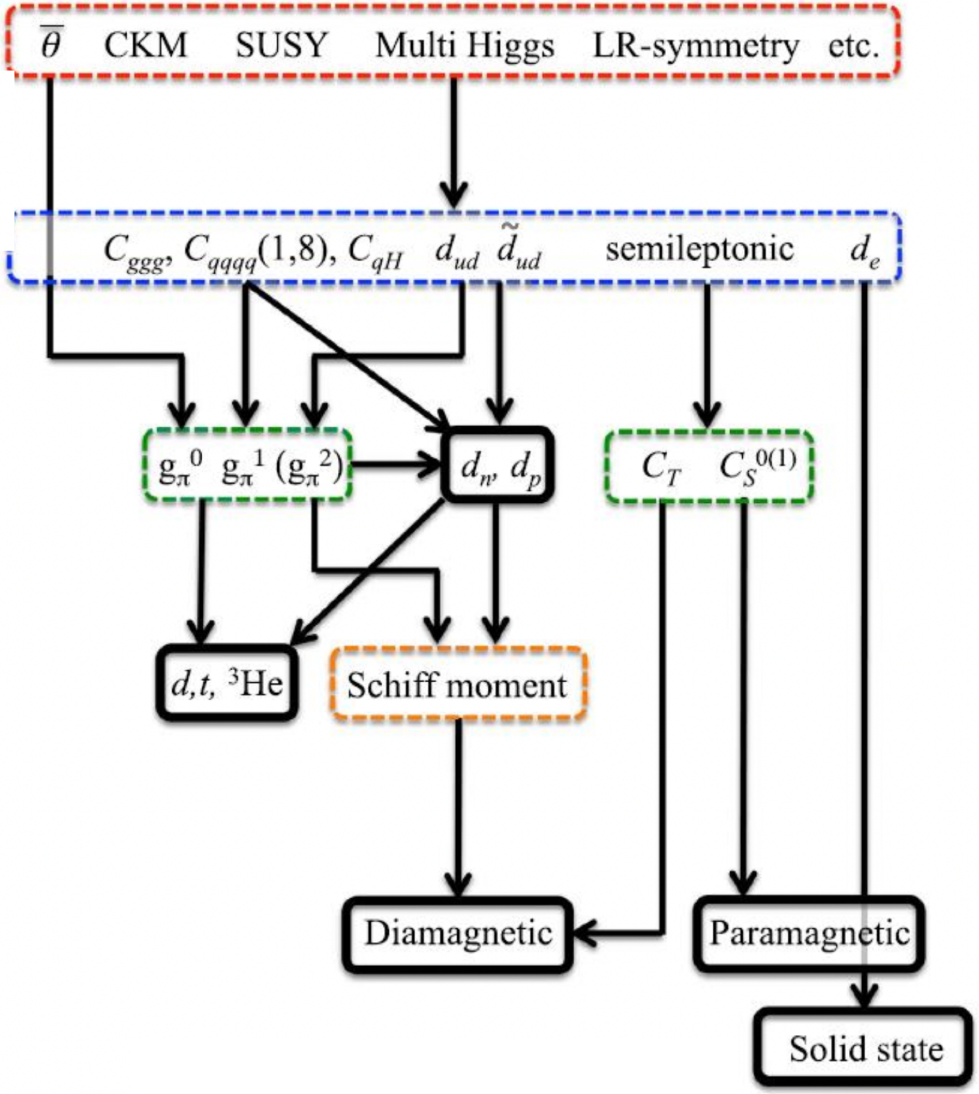
For nEDM ~ $d_n < 10^{-26}$ ecm:

$$\Lambda \sim 10 - 100 \text{ TeV}$$

Side Note: EFTs and EDMs cause interesting effects:

E.g. Scalar Leptoquarks would cause d_τ & d_n & flavor physics signals.

Dekens, DeVries, Jung, Vos, JHEP 01 (2019) 069



T. Chupp, PF, M.J. Ramsey-Musolf, J Singh, Rev. Mod. Phys. 91, 015001 (2019)

Coefficients and Experiments

e and μ EDM

Nuclear-spin-dependent e-N coupling C_T,

Nuclear-spin independent couplings C_S^0

Intrinsic quark EDMs and chromo EDMs

Meson-nucleon couplings $g_\pi^{0,1,(2)}$

... Linear equation system -> matrix...

- Paramagnetic atoms

$$d_{para} = \eta_{d_e} d_e + k_{C_S} \bar{C}_S$$

- Polar molecules

$$\Delta\omega_{para}^{\not{P}\not{T}} = \frac{-d_e E_{eff}}{\hbar} + k_{C_S}^{\omega} \bar{C}_S$$

- Diamagnetic atoms

$$d_{dia} = \kappa_S S(\bar{g}_\pi^{0,1}) + k_{C_T} C_T + \ldots$$

- Nucleons

$$d_{n,p} = d_{n,p}^{lr}(\bar{g}_\pi^{0,1}) + d_{n,p}^{sr}(\tilde{d}_{u,d}, d_{u,d})$$

- Fundamental fermions

$$d_e, d_\mu, (d_\tau)$$

...Higher orders (199-Hg!) :

$$d_A = (k_T C_T + k_S C_S) + \eta_e d_e + \kappa_S S + \text{h.o. (MQM)}$$

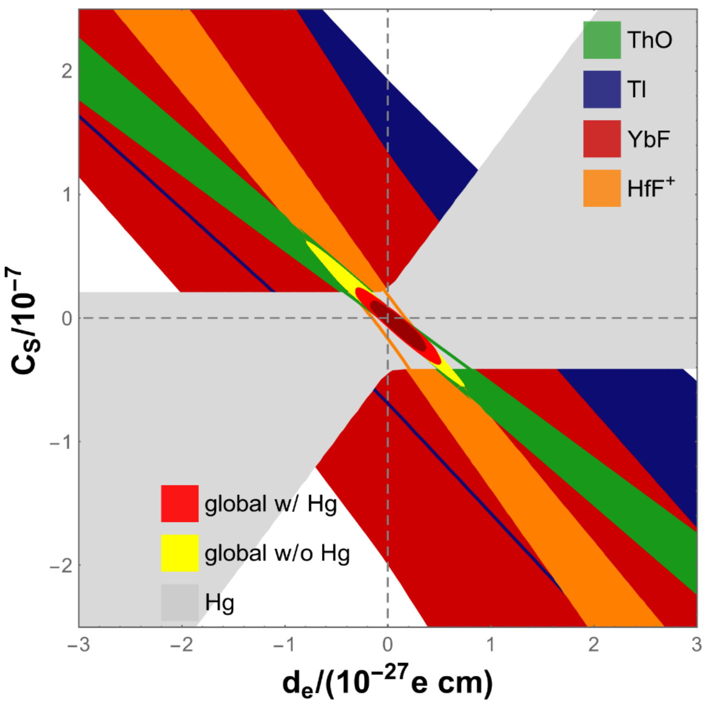
T. Chupp, PF, M.J. Ramsey-Musolf, J Singh, Rev. Mod. Phys. 91, 015001 (2019)

Analysis of EDM Results

Measured limits
(note: ‘sole-source‘ analysis)

System	Sensitivity	95% upper limit
Cs	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$	1.4×10^{-23}
	$d_e = (-1.5 \pm 5.6) \times 10^{-26}$	1.2×10^{-25}
Tl	$d_A = (-4.0 \pm 4.3) \times 10^{-25}$	1.1×10^{-24}
	$d_e = (6.9 \pm 7.4) \times 10^{-28}$	1.9×10^{-27}
YbF	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$	1.2×10^{-27}
ThO	$d_e = (-4.3 \pm 5.7) \times 10^{-30}$	1.1×10^{-29}
HfF^+	$d_e = (-1.3 \pm 2.6) \times 10^{-30}$	4.1×10^{-30} (90%)
^{199}Hg	$d_A = (2.2 \pm 3.1) \times 10^{-30}$	7.4×10^{-30}
^{129}Xe	$d_A = (1.4 \pm 8.6) \times 10^{-28}$	1.4×10^{-27}
^{225}Ra	$d_A = (-0.5 \pm 2.5) \times 10^{-22}$	5.0×10^{-22}
n	$d_n = (0.0 \pm 1.3) \times 10^{-26}$	1.8×10^{-26}
μ	$d_\mu = (0.0 \pm 0.9) \times 10^{-19}$	1.8×10^{-19}
Λ	$d_\Lambda = (-3.0 \pm 7.4) \times 10^{-17}$	7.9×10^{-17}

Parameters are not independent:
e.g. d_e as function of C_S



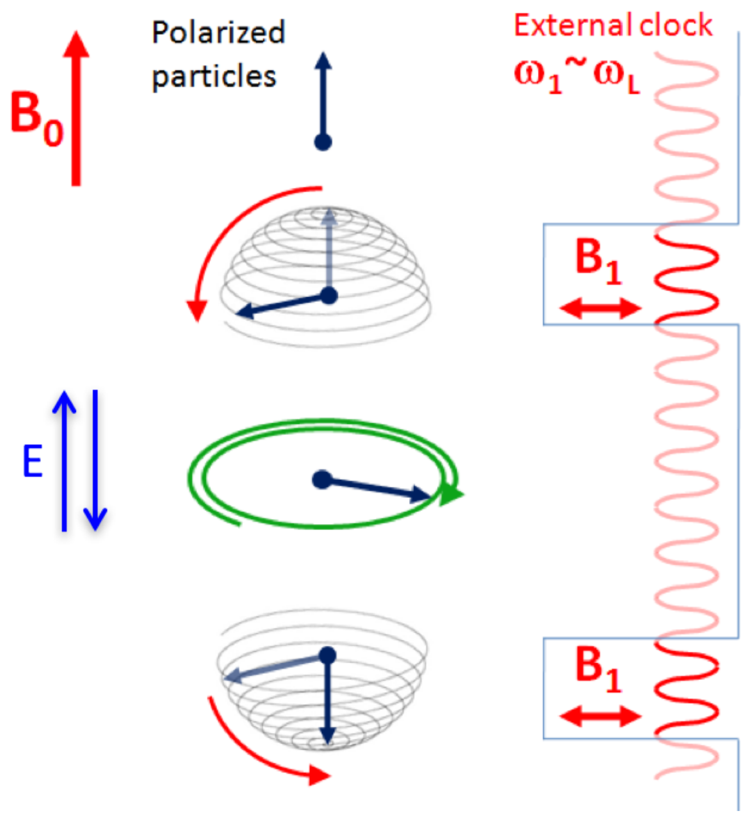
$$d_{\rm para}^{\rm exp} = d_e + \frac{\alpha_{C_S}}{\alpha_{d_e}} C_S$$

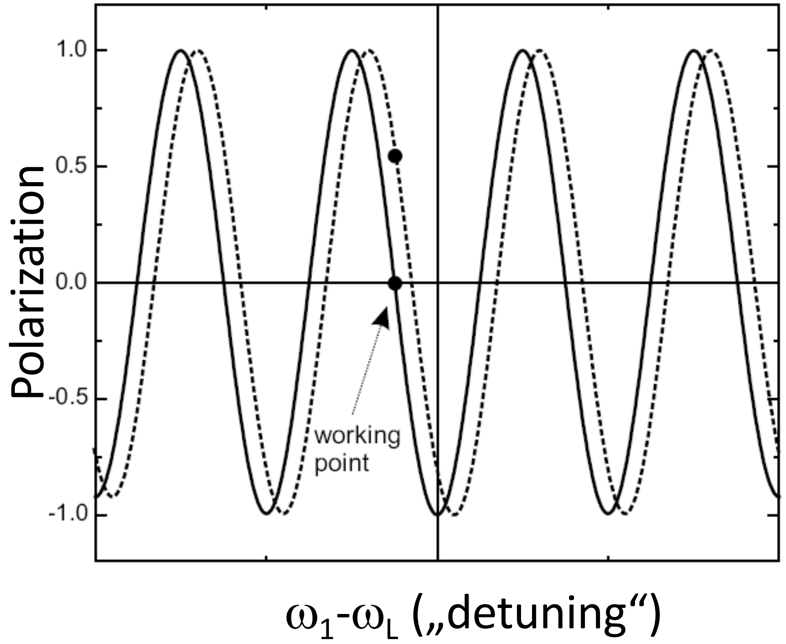
- **Many measurements needed with different systems**
- **Updated/new joint analysis needed...**

T. Fleig, M. Jung, JHEP 2018: 12

Measuring an EDM

Ramsey's Method:





$$\hbar\omega_L \sim \mu B + dE$$

Measuring an EDM

Orders of magnitude:

$$\mu_{\mathrm{N}} \times \frac{1\mu\mathrm{T}}{2\pi\hbar} = 8\ \mathrm{Hz}$$

$$10^{-26} e\ \mathrm{cm} \times \frac{1\ \mathrm{MV}}{m} \times \frac{1}{2\pi\hbar} = 24\ \mathrm{nHz}$$

Measuring an EDM *d*:

$$\delta d \sim \frac{h}{ET_2}\frac{1}{S/N}$$

$$\rightarrow \frac{h}{2ET_2}\frac{1}{\sqrt{\phi_n T_2}}$$

… “continuous” investigation of spin precession, limited by phase noise

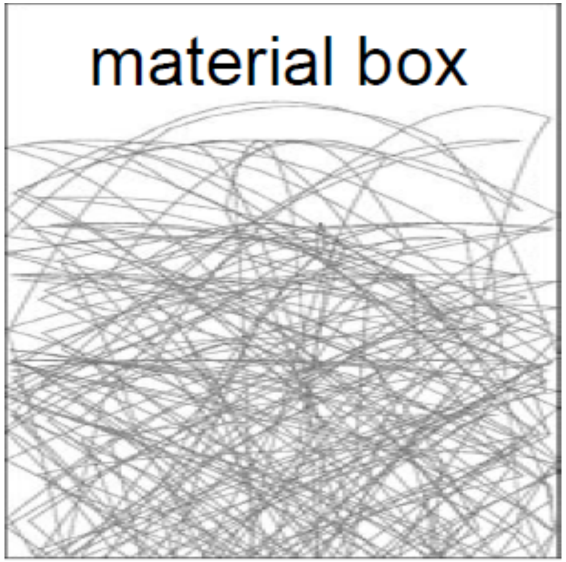
$$\rightarrow \frac{h}{2ET_2}\frac{1}{\sqrt{N_{\mathrm{n}}}}$$

… particle counting experiment, limited by the number of detected particles

Neutron EDM

Typical for ”next-gen”: factor 10 improvement envisaged (10^{-27} ecm)

Experiments: LANL, ILL/TUM, PSI, TRIUMF



- Trapped ultra-cold neutrons:
  - N ~ 10^{5-6} counted at end of Ramsey experiment
  - 10^4 repetitions ~ 100 days

- Magnetic fields:
  - Undetected field drifts: ~ 1 fT over 250 s

$$d_{false:\Delta B} = \frac{2\mu\Delta B}{4E}$$

  - T_2 in gradient is volume dependent
  - Magnetometers: ^{199}Hg, Cs, ^{129}Xe, ^{3}He, SQUIDs (in-situ or surrounding)

- A very delicate indirect systematic effect: Bloch-Siegert-shift

Eur. Phys. Lett. 116,43002 (2016).

Ramsey-Bloch-Siegert Shift

Most critical issue for next-generation measurements:

$$\Delta\omega = \frac{\omega_{xy}^2}{2(\omega_0 - \omega_r)}$$

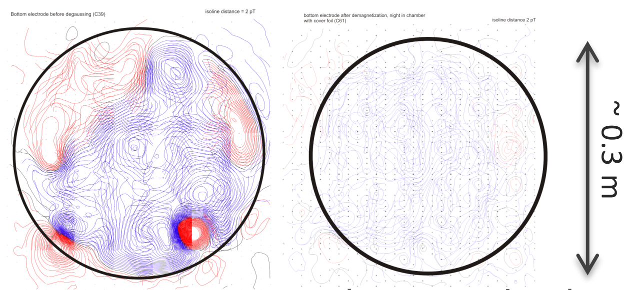
$$\omega_{xy}^2 = \left(\frac{\partial B_{0z}}{\partial z}\alpha\right)^2 + \left(\frac{E \times v}{c^2}\right)^2 + 2\frac{\partial B_{0z}}{\partial z}\alpha \cdot \frac{E \times v}{c^2}$$

Pendlebury et al., Phys. Rev. A ***70****, 032102 (2004)*

- dB/dz < 0.3 nT/m for 10^{-27} ecm statistical precision
- Consequence: “everything” in an experiment is magnetic!
- New issues? (e.g. Tsallis distributions)
  Eur. Phys. Lett. 116,43002 (2016).

Example:
Dipole fields in EDM chambers

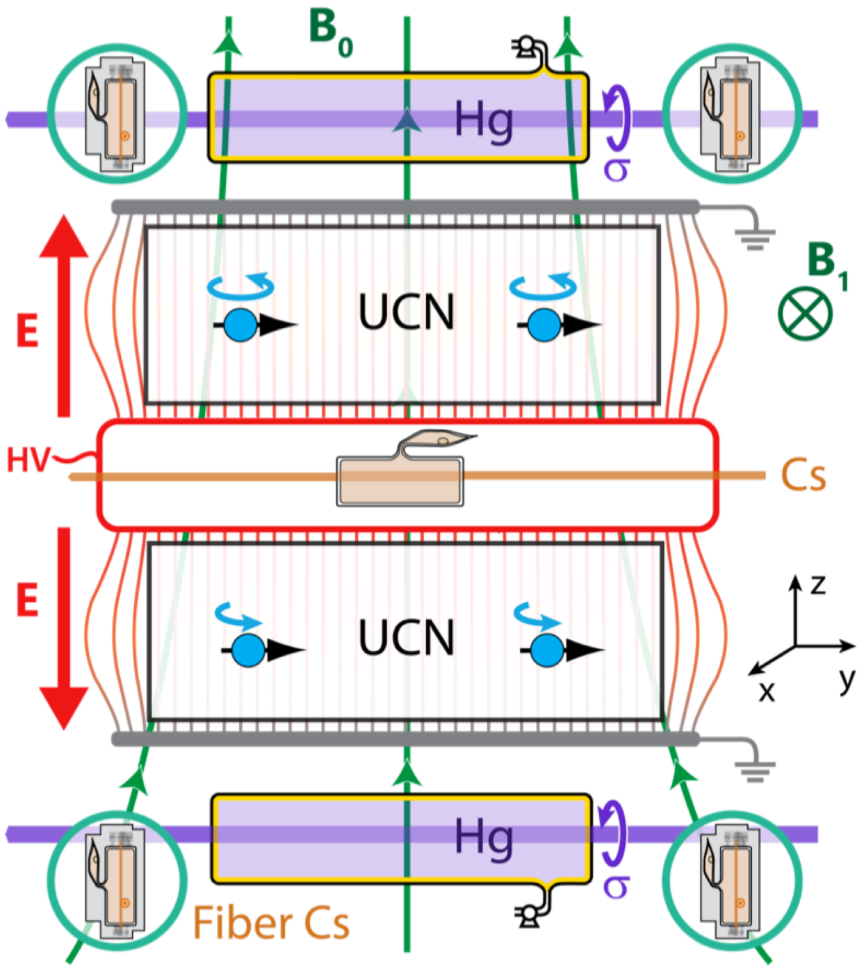
SQUID measurements of Sussex EDM electrodes @ PTB Berlin



20 pT in 3 cm ~ 5 x error budget!

Further: P. G. Harris et al., Phys. Rev. A 73, 014101 (2006), also: G. Pignol, arXiv:1201.0699 (2012).

The PanEDM Experiment



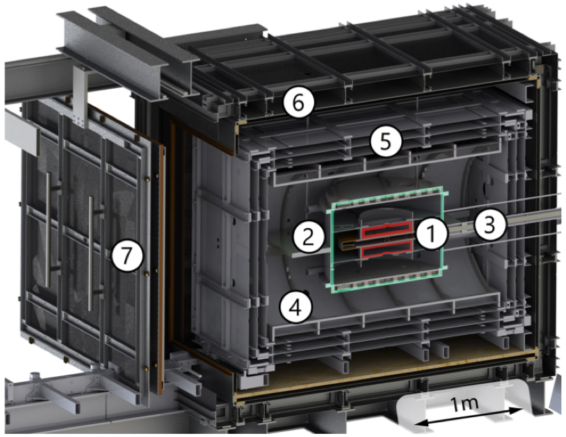
- Double chamber
- Gradient drift: < 5 fT/m in 250 s
- Magnetic shielding factor: $6 \cdot 10^6$ at 1 mHz
- < 100 pT residual field
- 10^{-4} relative homogeneity of 2 µT field
- Current status: testing of component groups with UCN

SuperSUN	**Phase I**
Saturated source density [cm^{-3}]	330
Diluted density [cm^{-3}]	63
Density in cells [cm^{-3}]	3.9
PanEDM Sensitivity [1σ, e cm]	
Per run	5.5×10^{-25}
Per day	3.8×10^{-26}
Per 100 days	3.8×10^{-27}

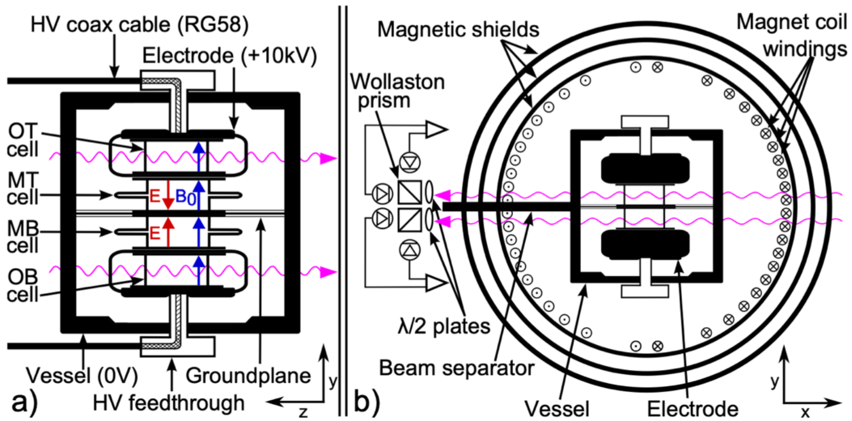
D. Wurm et al., EPJ Web of Conferences 219, 02006 (2019)

The PanEDM Experiment

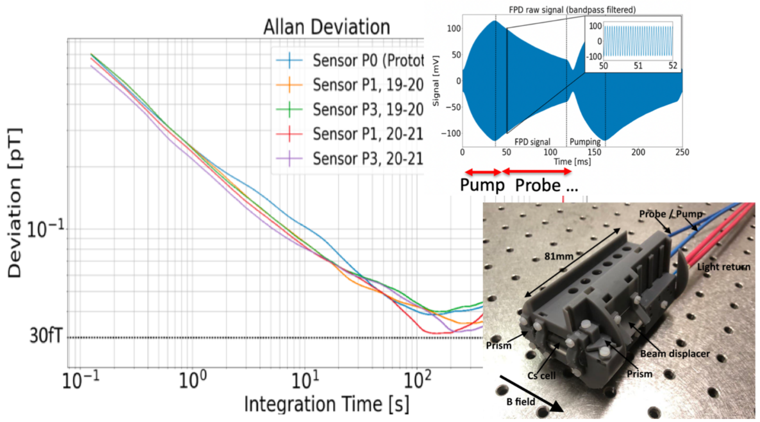
E.g.: Extreme magnetic shielding



Multiple measurement cells - ideas borrowed from 199Hg EDM:

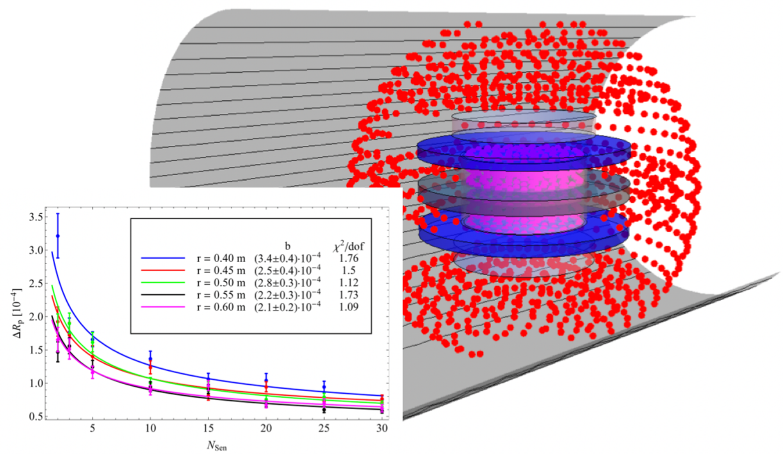


Atomic magnetometers



Spin off: medical imaging!

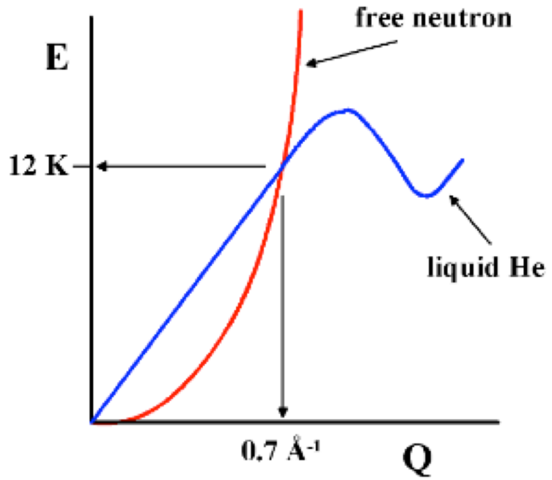
„Almost“ a 4-pi magnetometer

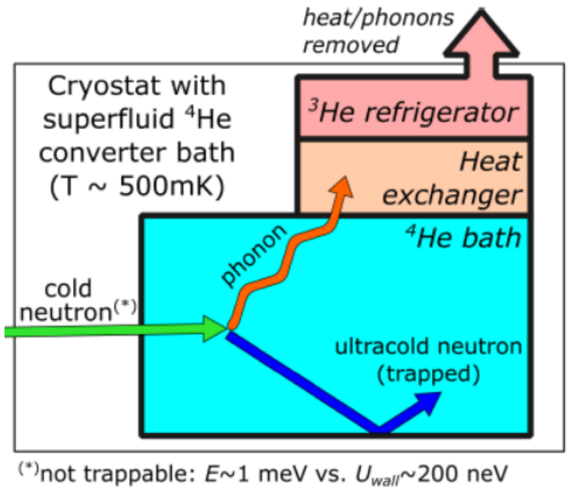


UCN for PanEDM: SuperSUN

The SuperSUN ultra-cold neutron source at ILL Grenoble: an incredibly strong ultra-cold neutron source (NEWS! Press release soon + paper to come…)

- UCN production in superfluid helium (apparently the best approach)
- UCN accumulation in superfluid helium
- Transfer of UCN to experiment into vacuum





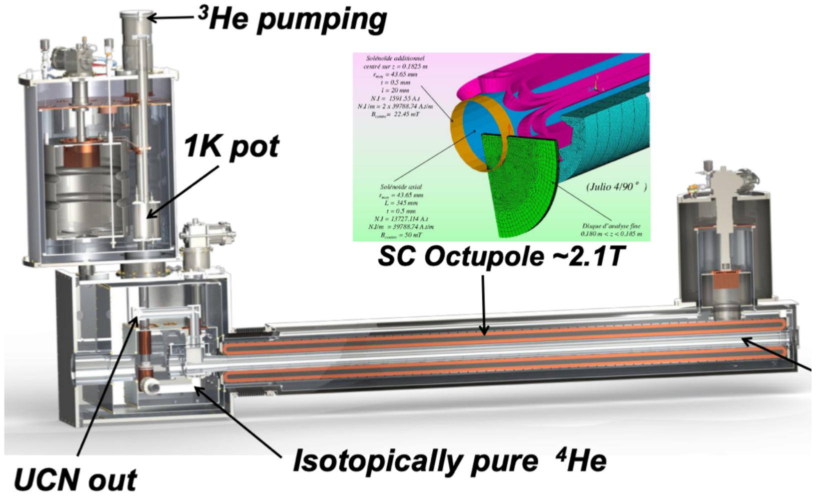


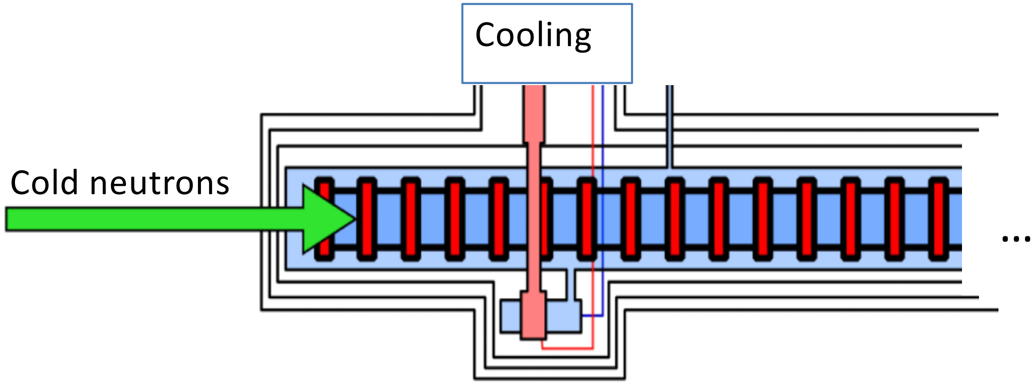
Figure credit: S. Degenkolb

Future Neutron EDM

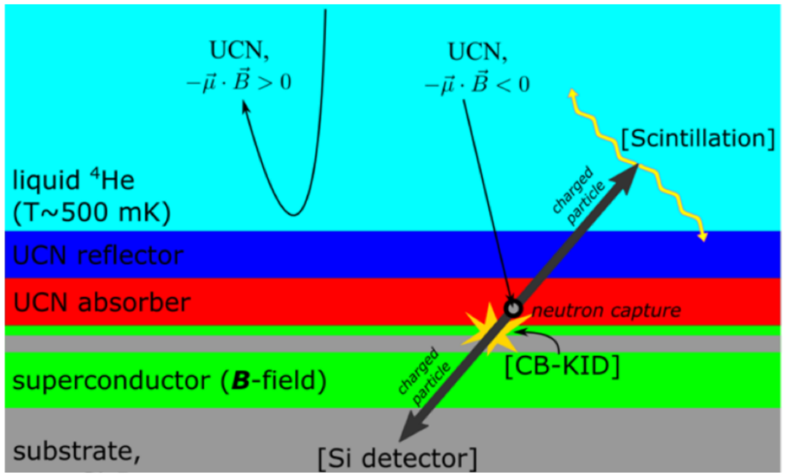
Factor 1000 improvement in statistics now seems *again* feasible

- High densities in superfluid helium and in comparable geometry demonstrated
- 100 EDM experiments in parallel
- No transport losses:
  - UCN produced directly in EDM cell
  - UCN detected directly in EDM cell
- “Perfect” mechanics of cells = enhanced storage
- Uses existing cold neutron beams

Multi-EDM chamber stack in superfluid He:



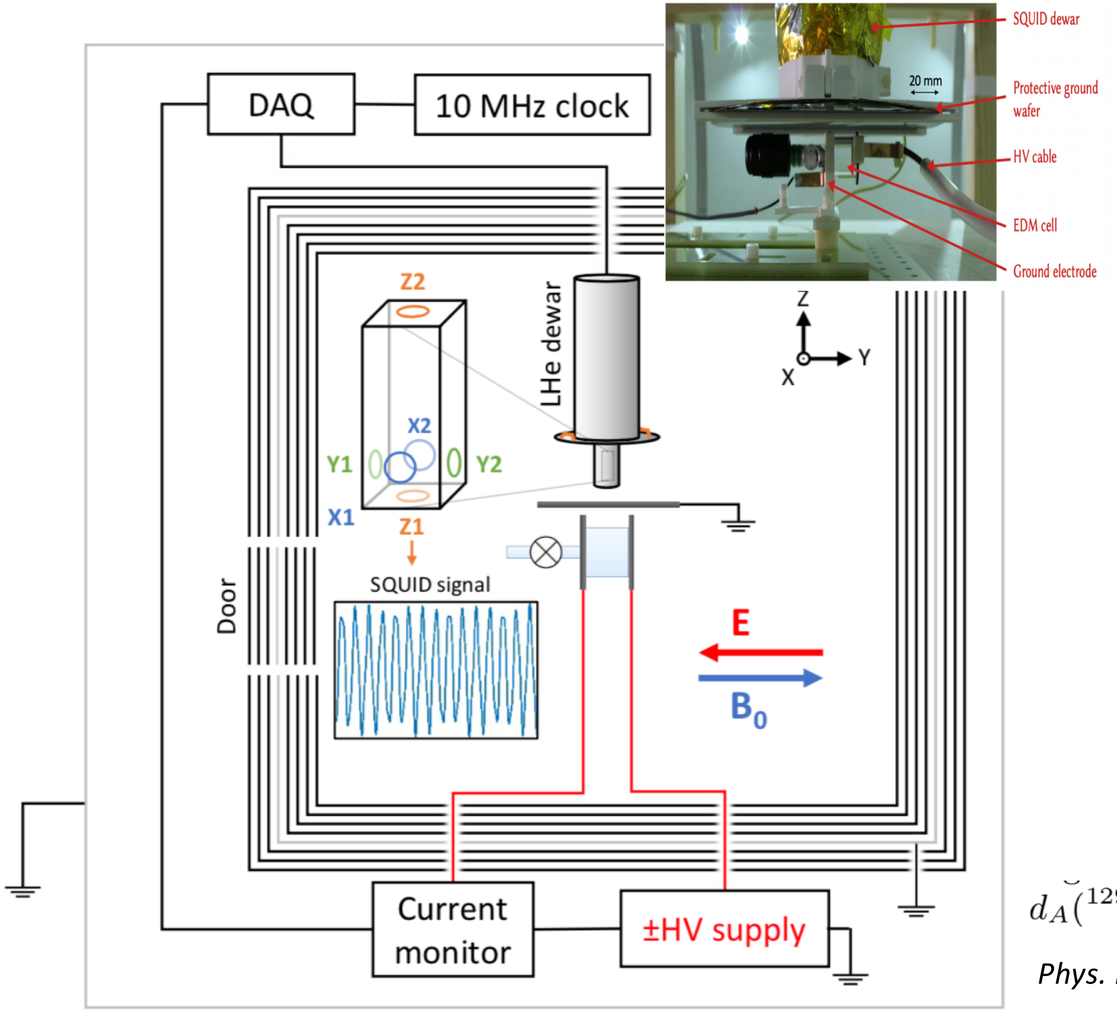
In-situ polarized UCN detection:



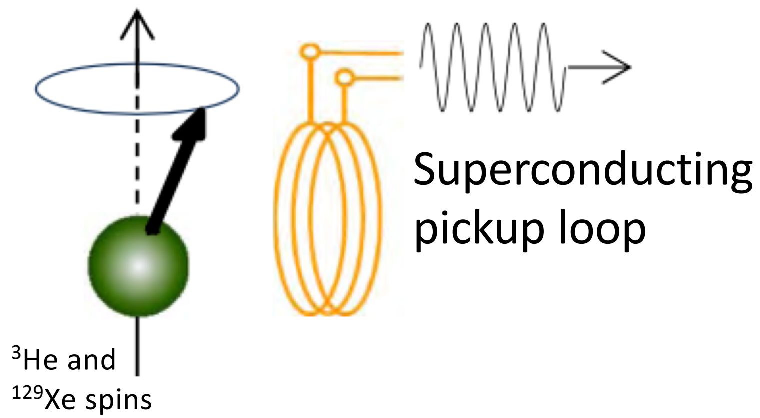
Experiment concept: S. Degenkolb, PF, O. Zimmer, EPJ Web of Conferences (2019)

Atom EDM: ^{129}Xe

SEOP-hyperpolarized 3-He / 129-Xe co-magnetometer



$$\sigma = \frac{\hbar}{2E}\delta\omega = \frac{\hbar}{2E}\frac{\epsilon}{T^{3/2}S\sqrt{N}}$$

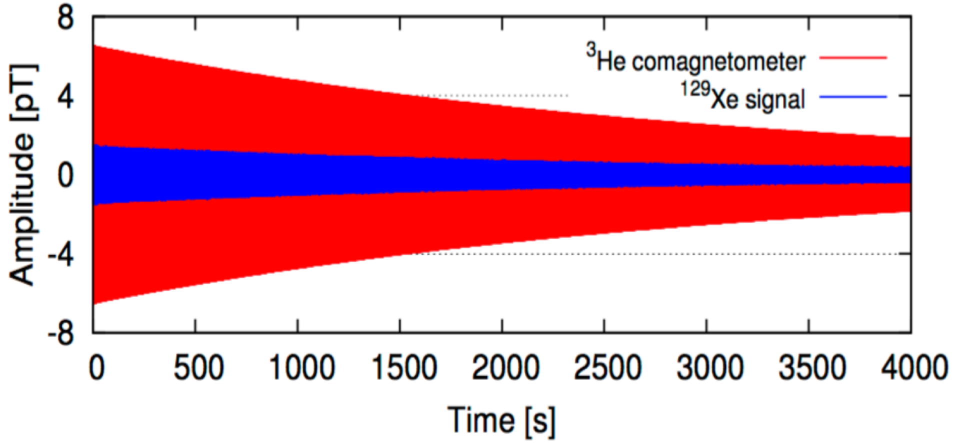


$$d_A(^{129}\mathrm{Xe}) = (0.26 \pm 2.33_{\mathrm{stat}} \pm 0.72_{\mathrm{syst}}) \times 10^{-27}\ e\,\mathrm{cm}$$

Phys. Rev. Lett. 123, 143003 (2019)

Atom EDM: ^{129}Xe

Raw data:



Systematic effects:

Source	Sys. Error (e cm)
Leakage current	1.2×10^{-28}
Charging currents	1.7×10^{-29}
$\vec{E}$-correlated cell motion (rotation)	4.2×10^{-29}
$\vec{E}$-correlated cell motion (translation)	2.6×10^{-28}
Comagnetometer drift	6.6×10^{-28}
$\lvert\vec{E}\rvert^2$ effects	1.2×10^{-29}
$\lvert\vec{E}\rvert$ uncertainty	2.6×10^{-29}
Geometric phase	$\leq 2 \times 10^{-31}$
Total	7.2×10^{-28}

Next version currently being set up, test runs 2024

Required:

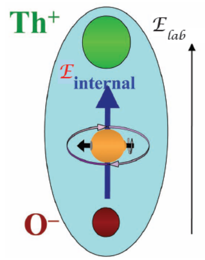
- Extremely stable and low gradient environment: new specialized lab being built
- Highly sensitive sensing: e.g. 4-pi detection and AI, for 3D reconstruction of precessing dipoles and distortions

Community:

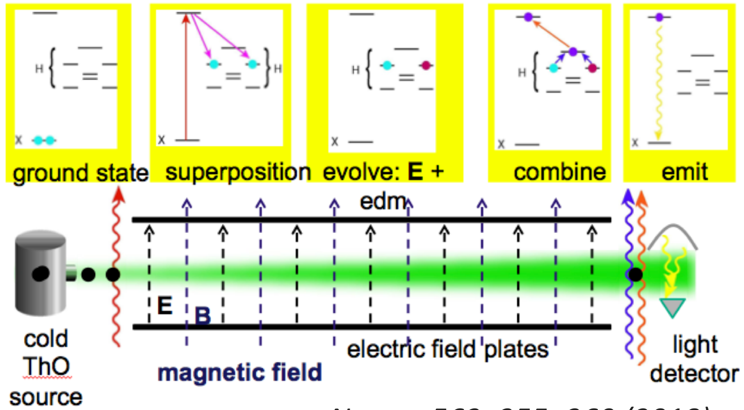
- HeXe experiment
- MiXed experiment

Molecule EDM Searches

Polar molecules:
- ~ 100 GV/cm internal electric field,
- polarizable with small ext. E-field
- Small magnetic moment = low effect of B-field quality
- High Z: enhancement
- Lasers to select states

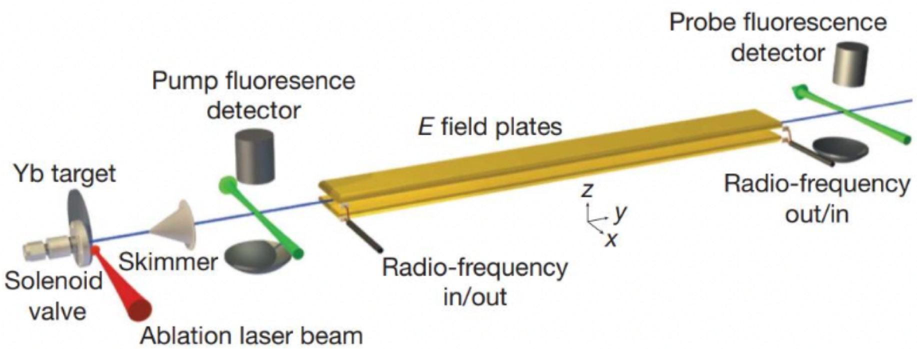


E.g. ThO (ACME Experiment)
- Spin precession in cryogenic beam

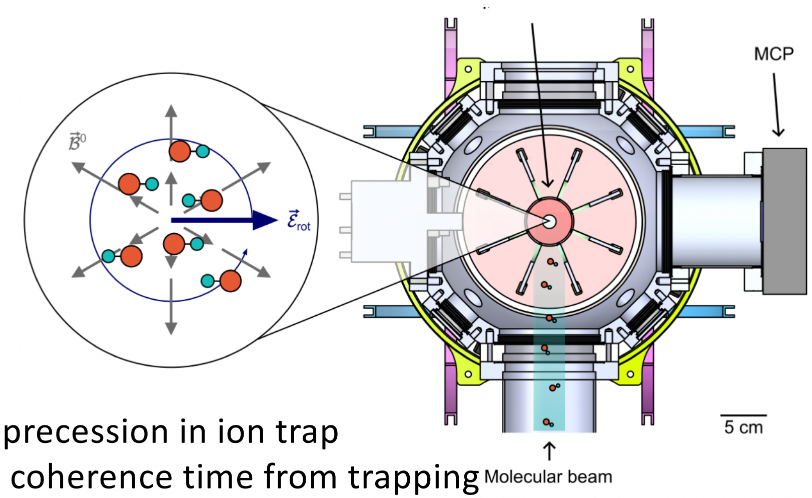


Nature 562, 355–360 (2018)

YbF:
•Spin precession in pulsed supersonic beam
•First to beat atomic experiments



HfF+:



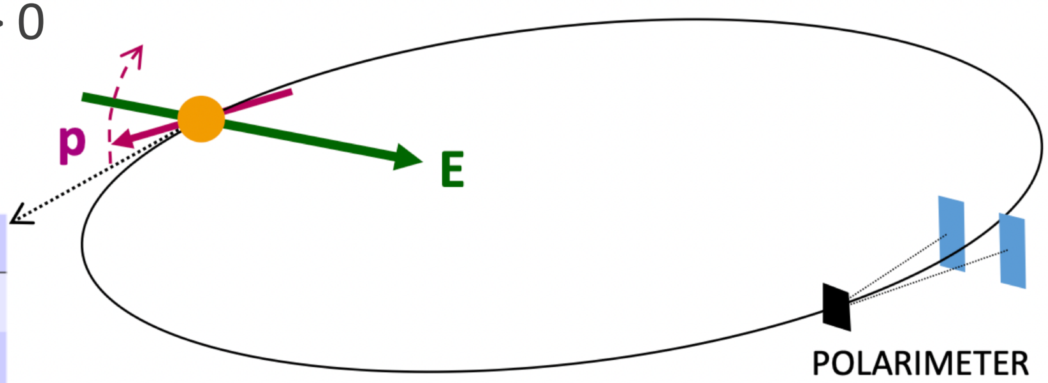
•Spin precession in ion trap
•Long coherence time from trapping

https://arxiv.org/pdf/2212.11841.pdf

Electrostatic Storage Ring Searches

Relativistic motion causes B field in frame of moving particle

- Frozen horizontal spin precession: p || s at magic momentum
- EDM turns s out of plane
- Purely electric ring only for G > 0
- E and B ring for other isotopes



	$G = \frac{g-2}{2}$	p/GeV/c	E_R/MV/m	B_V/T
proton	1.79	0.701	10	0
deuteron	−0.14	1.0	−4	0.16
^{3}He	−4.18	1.285	17	-0.05

$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s}$$

$$\vec{\Omega} = \frac{e\hbar}{mc}\left[G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E} + \frac{1}{2}\eta(\vec{E} + \vec{v} \times \vec{B})\right]$$

$$\vec{d} = \eta\frac{e\hbar}{2mc}\vec{S}, \quad \vec{\mu} = 2(G+1)\frac{e\hbar}{2m}\vec{S}, \quad G = \frac{g-2}{2}$$

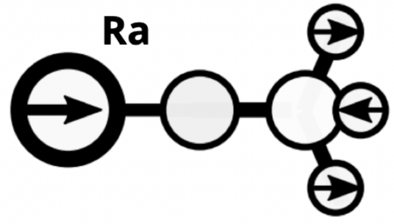
E.g. Rev Sci Instrum 87, 115116 (2016), https://arxiv.org/pdf/2205.00830.pdf

V. Bargmann, L. Michel and V. L. Telegdi, Phys. Rev. Lett. 2 (1959) 435.

Advances in AMO: new EDM Searches

Laser cooling:
Longer observation time (linear)
Higher particle density (sqrt)
Much longer coherence time (linear)

$RaOCH3^+$ molecule ion

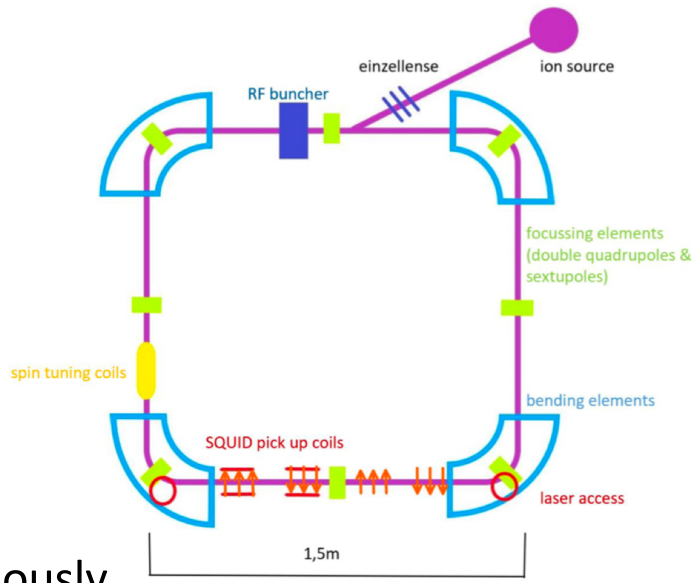


Laser trapping:
Profits from other fields: rapid advances in technology
Allows assembly of molecules

Polyatomic molecules:
Cooling techniques also work for complicated molecules
Large internal fields also present
Allows combination of deformed nuclei and trapping

Q. Sci. & Tech. 5, 044011 (2020)

Electrostatic storage ring as particle trap:
Non-relativistic, fully electrostatic particle trapping
Laser and SQUID access to atomic state manipulation
Hours of storage times, different configurations simultaneously



EPJ Web of Conferences 282, 01017

Side Note: Exotic Physics Searches

Axionlike particle coupling to (electron) spins: $\mathcal{L} = g_{a\psi\psi}\partial_\mu a\bar{\psi}\gamma^\mu\gamma_5\psi$

The gradient of an (ultralight) Axion field acts on spins:

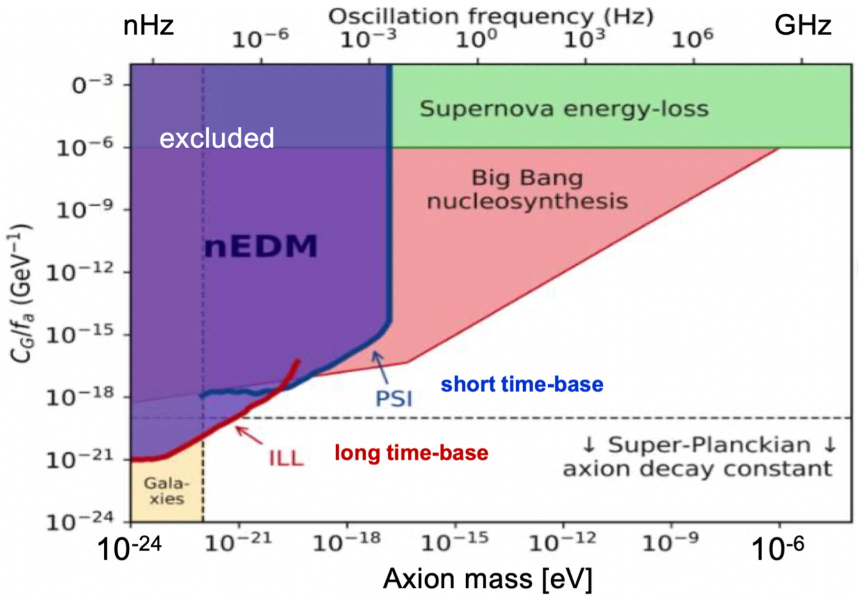
$$H = -g_{aee}\nabla a \cdot \sigma \quad \Leftrightarrow \quad H = -\mu\, B \cdot \sigma$$

Observable as oscillating magnetic field:

$$\mu B_{eff} = g_{aee} a_o m_a \vec{v} cos(m_a t) = g_{aee}\sqrt{\rho_{DM}}\vec{v} cos(m_a t)$$

Natural scale ~ 10^{-20} T

Similar physics: nuclear coupling
-> oscillating EDMs…



Abel et al., PRX7 (2017) 041034

Summary

- EDMs should be measured with several systems: together with EFT parameters, this is a powerful tool to search for new physics
- Neutron EDM searches have significant potential *again*
- The experimental field is recently progressing fast and with lots of innovations: cool ideas with
  - polyatomic molecules
  - very heavy isotopes like 225-Ra
  - particle trapping
  - electrostatic storage rings
- EDM searches are extremely advanced *Quantum Sensing* experiments, with spin-offs for ALP searches and applied technology like medicine