Electric Dipole Moment searches using atoms, neutrons and molecules:

State of the art and new directions using rare isotopes

Florian Kuchler – TRIUMF, June 2020

Outline

- Fundamental symmetries and the Standard Model (SM)
- Electric dipole moments (EDMs) in the SM and new physics reach
- EDM experiments:
  - History, overview and measurement technique
  - State-of-the-art: xenon, neutron
- Fundamental symmetry tests with rare isotopes
  - State-of-the-art: radium, ThO (electron EDM)
  - New directions

Symmetries in physics

Feynman (following Weyl)

> "A thing is symmetrical if one can subject it to a certain operation and it appears exactly the same after the operation."

R. P. Feynman, R. B. Leighton, M. Sands, The Feynman lectures on physics, Addison-Wesley, 1965

Translation in space $x \to x + \Delta x$
Translation in time $t \to t + \Delta t$
Rotation by fixed angle $\vec{r} \to \vec{r}e^{i\theta}$

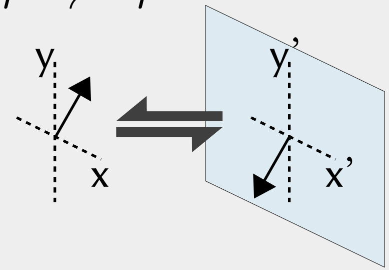
$\xrightarrow{\text{Noether's theorem}}$

Energy conservation
Momentum conservation
Angular momentum conservation

Discrete symmetries

Parity P

$\vec{r} \to -\vec{r}$



Charge conjugation C

Time reversal T

$t \to -t$

We do like symmetries,
but it turned out to be more complicated…

A history of testing fundamental symmetries

1956/57

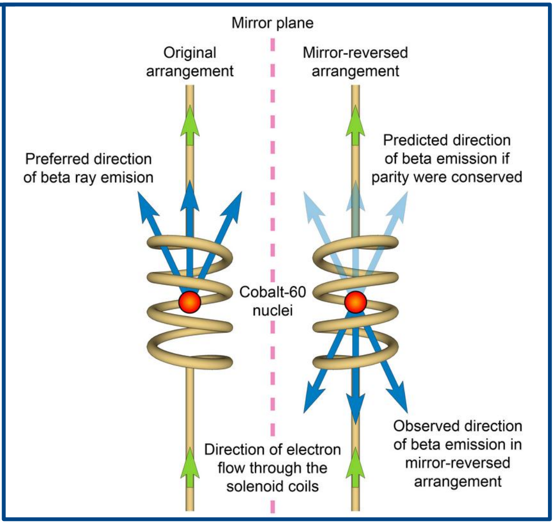
PARITY NOT CONSERVED !
Jan 27. 1956.

Parity violation in weak interaction
→ Lee & Yang Nobel Prize in 1957

Lee, Phys. Rev. **104**, 254 (1956)
Wu, Phys. Rev. **105**, 1413 (1957)

C and P violation in meson decay

Garwin, Phys. Rev. **105**, 1415 (1957)



1964

CP violation in kaon decay
→ Cronin & Fitch Nobel Prize 1980

Christenson, Phys. Rev. Lett. **13**, 138 (1964)

2001

CP violation in B meson decay

Aubert, Phys. Rev. Lett. **86**, 2515 (2001)
Abe, Phys. Rev. Lett. **87**, 091802 (2001)

2012

Direct **T violation** observed in B^0 meson system

Lee, Phys. Rev. Lett. **109**, 211801 (2012)

2014

CP violation in strange B meson decays

Aaij, Phys. Rev. Lett. **110**, 221601 (2014)

2019

CP violation in D meson decays

Aaij, Phys. Rev. Lett. **122**, 211803 (2019)

2020

Neutrino/anitneutrino discrepancies
Indication of **CP violation in lepton sector**

Abe (T2K), Nature **580**, 7803 (2020)

Breaking symmetries in the Standard Model

Weak interaction maximally breaks parity and violates CP symmetry:
CKM matrix accounts for CP violation through phase δ:

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

Experiments: $\theta_{12} = 13.04 \pm 0.05^\circ$ $\theta_{13} = 0.201 \pm 0.011^\circ$ $c_{ij} = \cos\theta_{ij}$

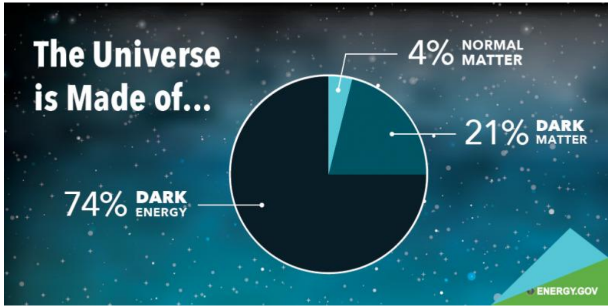
$\theta_{23} = 2.38 \pm 0.06^\circ$ $\delta = 1.20 \pm 0.08$ rad $s_{ij} = \sin\theta_{ij}$

Θ-term in QCD

$$\mathcal{L}_\theta^{\mathrm{CPV}} = \theta \frac{g_s^2}{32\pi^2} \epsilon^{\mu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta}$$

CPT theorem

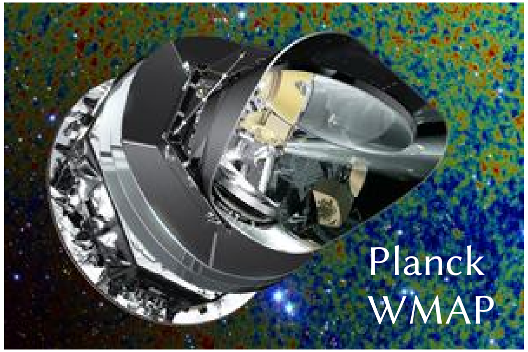
- CPT symmetry is conserved (required for local Lorentz invariance of quantum field theories)
  → T violation = CP violation
- Experimental tests compare matter vs antimatter and so far confirm CPT conservation (e.g. ATRAP, BASE, ALPHA, ASACUSA, GBAR)



Physics beyond the SM required to solve remaining puzzles, e.g. the nature of dark matter and dark energy

→ Search for new particles and interactions

The mystery of the missing antimatter

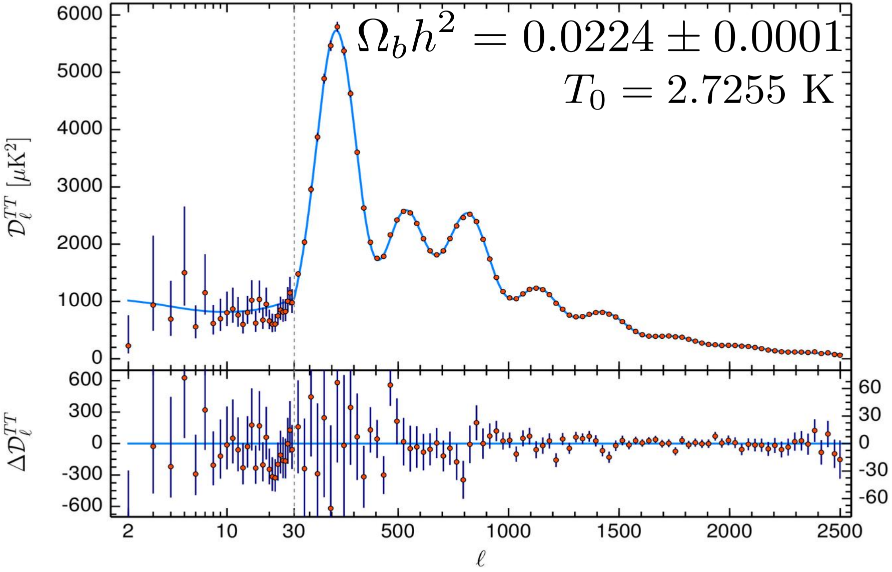


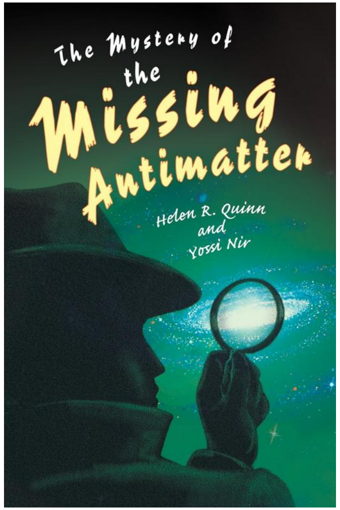
Baryon-to-photon ratio: CMB/BBN SM expectation

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} = 6.15 \times 10^{-10} \qquad \approx 10^{-18}$$

Dine, Rev. Mod. Phys. **76**, 1 (2003)
Iocco et al, Phys. Rep. **472**, 1 (2009)

Planck 2018, arxiv:1807.06209 (2019)





Sakharov criteria:

Sakharov, Pisma Zh.Eksp.Teor.Fiz. **5**, 32 (1967)

1) Baryon number violation
→ Sphaleron processes at extreme temperatures

2) Out of thermal equilibrium
→ first order phase transition in Early Universe

3) C and CP violation
→ not sufficient in SM

P-, CP violation and Electric Dipole Moments

Electric dipole moment

$$\vec{d} = \int \vec{r}\rho_{\mathrm{q}} d^3 r = d\frac{\langle\vec{J}\rangle}{J}$$

		P	T
Magnetic field	**B**	+	-
Electric field	**E**	-	+
Angular momentum	**J**	+	-
	B.J	+	+
	E.J	-	-

Note: EDM points along total angular momentum vector (or spin)
⟶ use systems with J ≠ 0

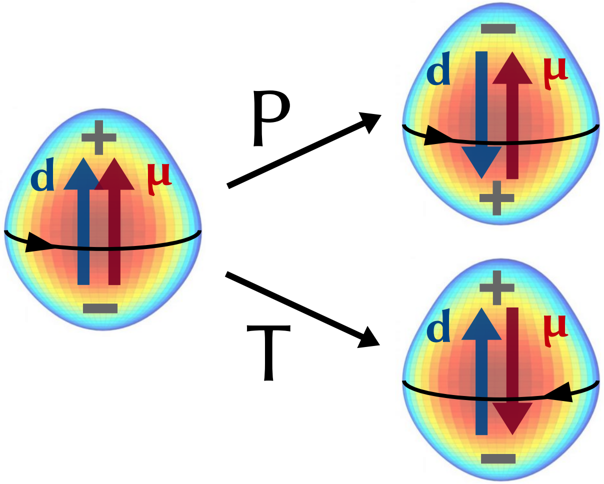
Hamiltonian $$\mathcal{H} = -\mu\vec{B}.\frac{\vec{J}}{J} - d\vec{E}.\frac{\vec{J}}{J}$$

Invariant under P only if d=0

EDMs are a sensitive direct probe of new physics ("flavour-diagonal")

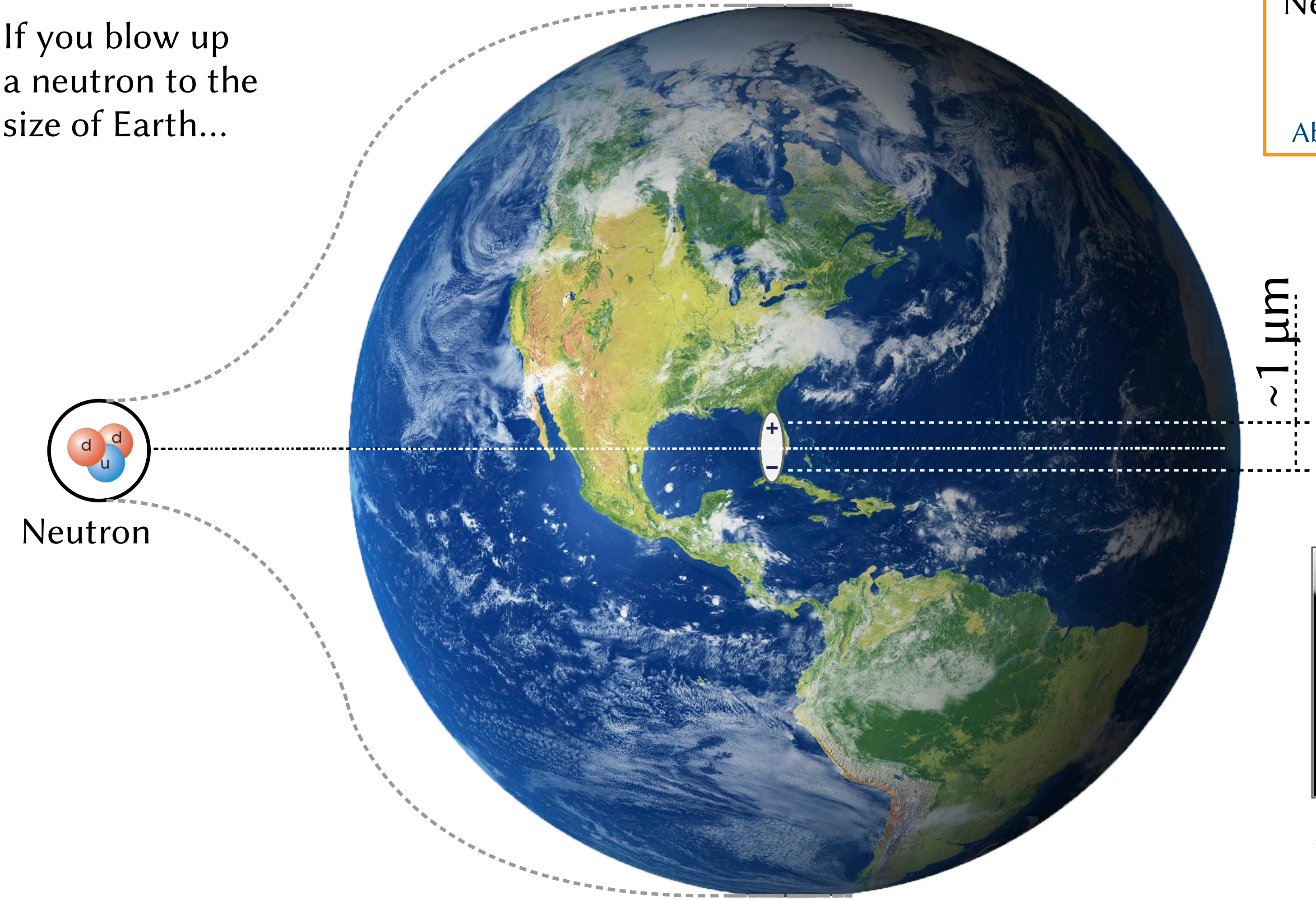
Many new physics models require larger EDMs
⟶ Even zero results strongly constrains new physics models

Khriplovich, "CP violation without strangeness", Springer (1997)
Chupp, Rev. Mod. Phys. **91**, 015001 (2019)



Scale of EDM sensitivity: Neutron EDM limit

If you blow up
a neutron to the
size of Earth…

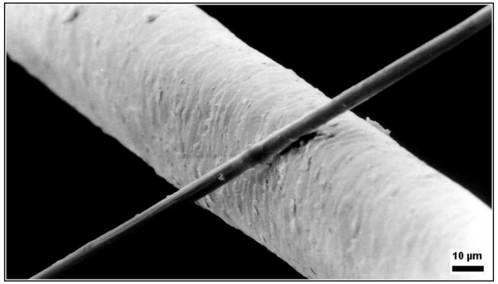


Neutron EDM limit (90% CL):

$$|d_n| \leq 1.8 \times 10^{-26} \ e\mathrm{cm}$$

Abel, Phys. Rev. Lett. **124**, 081803 (2020)

… an EDM of 10^{-26} *e*cm corresponds to separation of opposite electric charges by ~1 μm



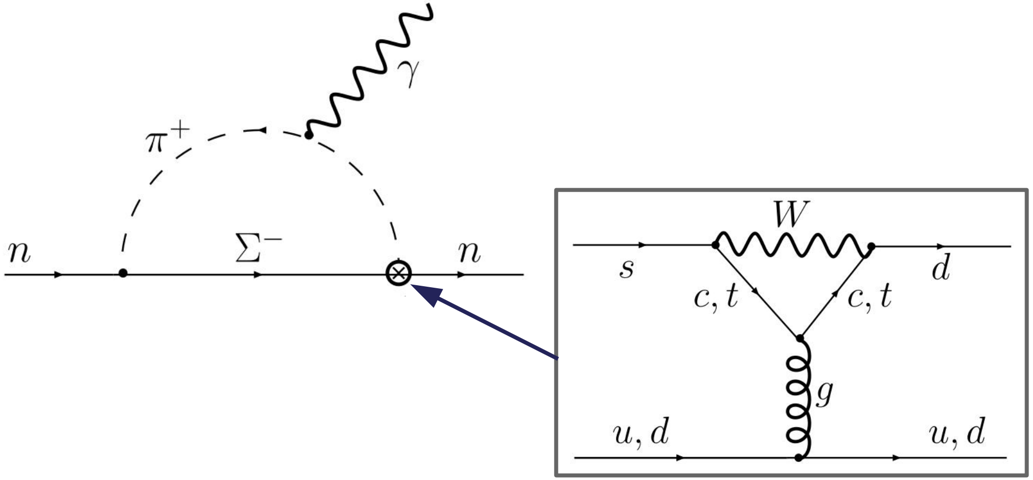
6 μm diameter carbon filament, compared to 50 μm diameter human hair

Generating a neutron EDM within the Standard Model

CKM matrix

EDMs generated only at higher loop levels
⟶ Contribution to nEDM from CKM:

$$d_n^{CKM} \sim 10^{-32}\ ecm$$



Khriplovich, Phys. Lett. B **109**, 490 (1982)
Pospelov, Annals Phys. **318**, 119 (2005)

Θ-term in QCD

Neutron EDM result constrains CP violation in strong interactions

$$d_n^{\text{QCD}} \sim \bar{\theta} \cdot (6 \times 10^{-17})\ ecm \Longrightarrow |\bar{\theta}| < 10^{-10}$$

unnaturally small - ”Strong CP problem”
⟶ introducing a new particle to restore naturalness: axions

Peccei, Phys. Rev. Lett. **38**, 1440 (1977)

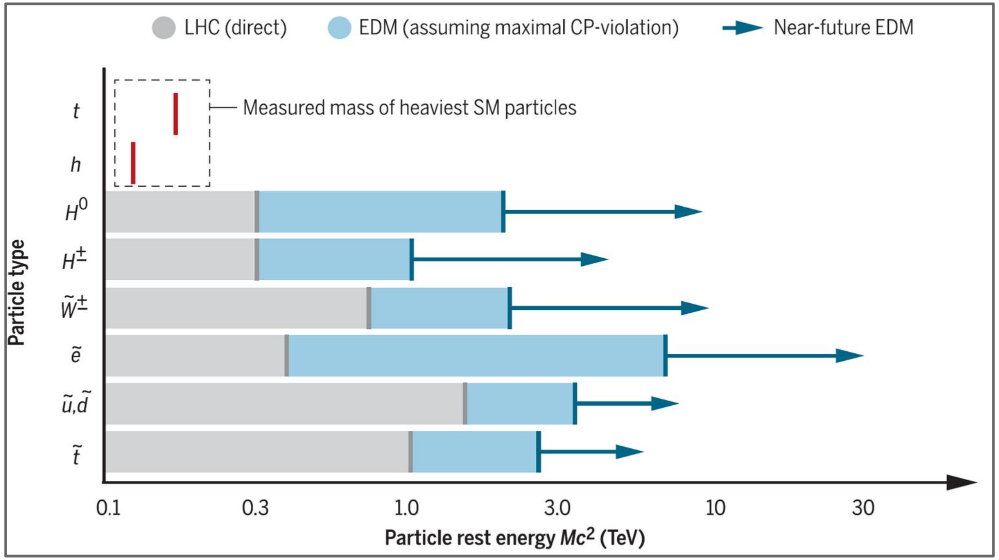
Impact of EDM results and energy reach

Typical EDM sensitivities	10^{-26} ecm – 10^{-29} ecm
Typical energy shifts	10^{-18} eV – 10^{-25} eV
High energy frontier	10^{12}-10^{13} eV

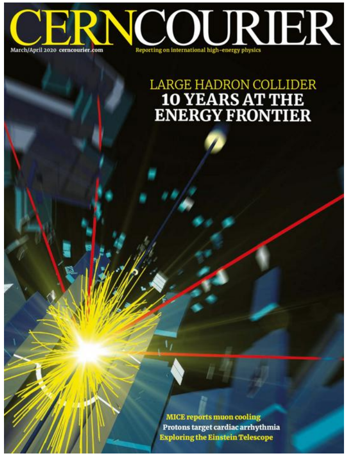
⟶ no signs of new physics at highest energies (yet)

Probing physics at the intensity/precision frontier:

Energy reach of EDM searches



DeMille, Science **357**, 990–994 (2017)



Electron EDM probes new particles of mass M

$$d_{\mathrm{e}} \propto \frac{1}{M^2}$$

⟶ limit of $|d_e| < 10^{-28}$ ecm implies M ≥ 1-2 TeV

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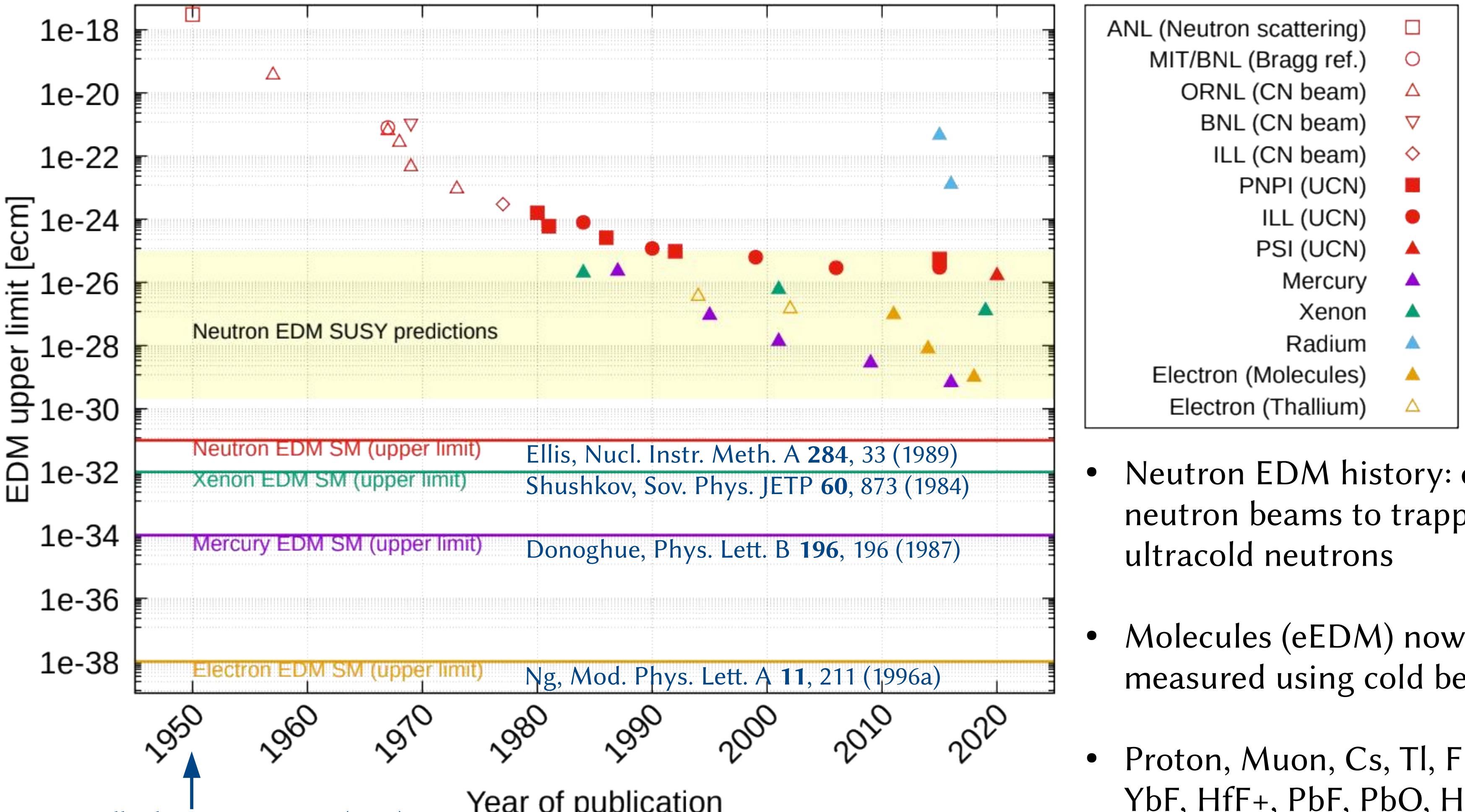
NEWS · 19 JUNE 2020

CERN makes bold push to build €21-billion super-collider

European particle-physics lab will pursue a 100-kilometre machine to uncover the Higgs boson's secrets – but it doesn't yet have the funds.

16 TeV ⟶ 100 TeV

History of EDM searches and Standar Model predictions



Ellis, Nucl. Instr. Meth. A **284**, 33 (1989)

Shushkov, Sov. Phys. JETP **60**, 873 (1984)

Donoghue, Phys. Lett. B **196**, 196 (1987)

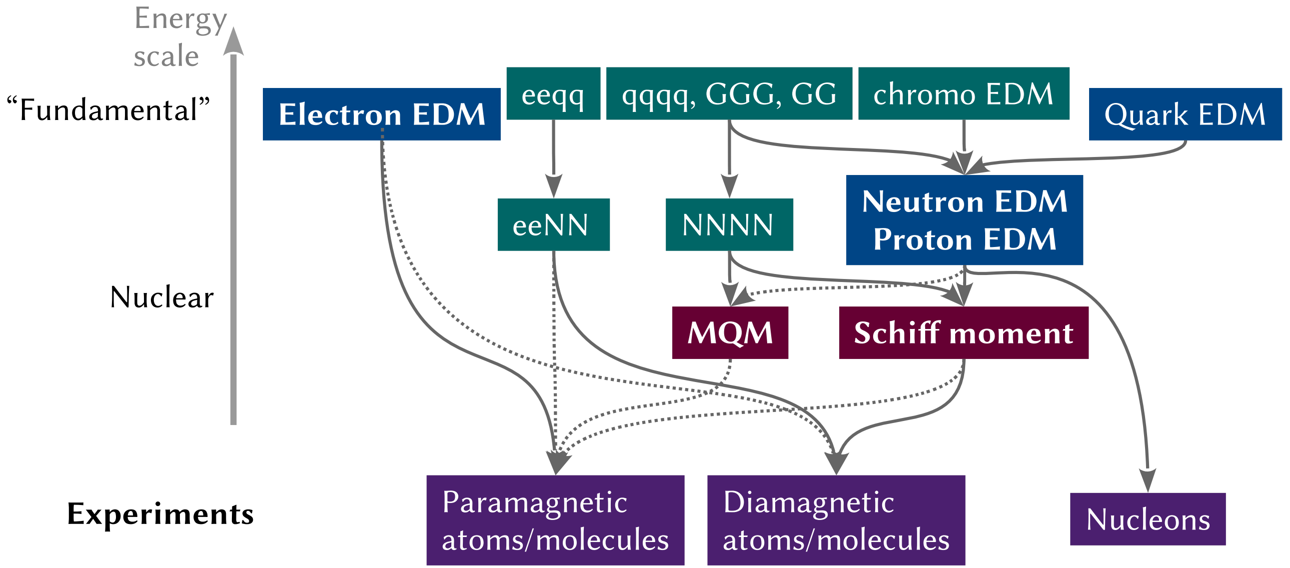
Ng, Mod. Phys. Lett. A **11**, 211 (1996a)

Purcell, Phys. Rev. **78**, 807 (1950)

- Neutron EDM history: cold neutron beams to trapped ultracold neutrons
- Molecules (eEDM) now measured using cold beams…
- Proton, Muon, Cs, Tl, Fr, Rn, TlF, YbF, HfF+, PbF, PbO, HfF

CP violation sources in different systems

Each system is sensitive to other underlying sources of CP violation:



"Fundamental" level

- EDMs of electrons, quarks
- CP odd interactions
  - electron-quark
  - quark-quark
  - gluon-gluon(-gluon)
- Chromo EDM (quark-gluon)

Nuclear level

CP odd nuclear moments:
  - magnetic quadrupole moment (MQM)
  - Schiff moment

Measured EDM limit yields constraints on CP odd sources:

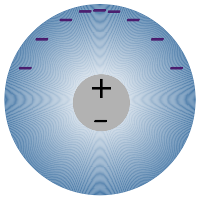
1) **Sole source** - under assumption of each contribution being the limiting one

2) **Global analysis** - combination of experimental EDM limits

Chupp, Phys. Rev. C **91**, 035502 (2015)

Nuclear Schiff moment

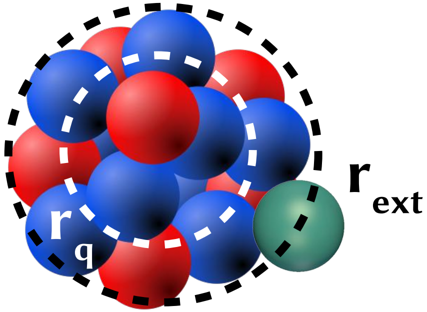
Schiff's theorem: EDM of a nucleus is perfectly shielded by atomic electron cloud
→ no nuclear EDM observable!



Finite size and relativistic effects
→ nuclear Schiff moment (P, T odd) induces observable atomic EDM

e.g. for unpaired nucleon (I=1/2; L=0):

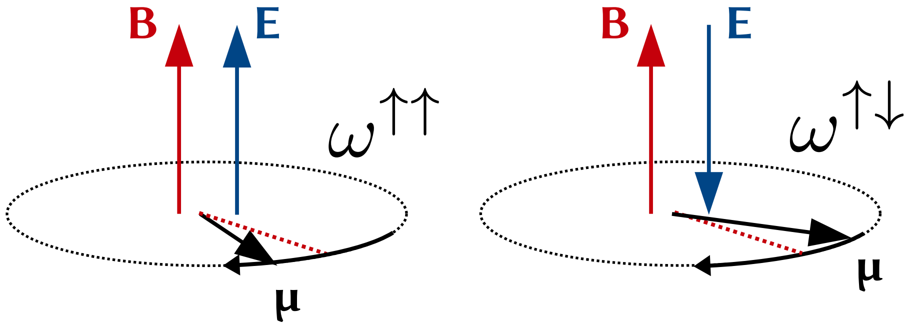
$$S \propto \left(r_{\mathrm{ext}}^2 - r_{\mathrm{q}}^2\right) \propto A^{2/3}$$



Schiff, Phys. Rev. **132**, 2194 (1963)
Sandars, Phys. Lett. **14**, 194 (1965)

Basic EDM measurement method

Spin precession perpendicular to ultra-low magnetic (1 μT) and high electric fields (~ 10 kV/cm)



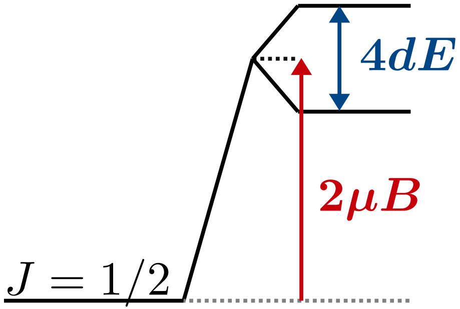
e.g. polarized sample of F = S = ½

$$\Delta\omega = \omega^{\uparrow\uparrow} - \omega^{\uparrow\downarrow} = \frac{4d|E|}{\hbar} + \gamma\delta B$$

e.g. for ^{129}Xe: $d \approx 10^{-27}\,\mathrm{ecm} \Longleftrightarrow \sigma_\nu \approx 10\,\mathrm{nHz} \Longleftrightarrow \delta B \approx 0.1\,\mathrm{fT}$

→ 10 nHz = one turn every three years

→ Systematics arise from magnetic field variations correlated with electric field reversal



Fundamental sensitivity of EDM searches

	Atoms (e.g. ^{129}Xe)	Ultracold neutrons	Molecules (eEDM)	
Fundamental sensitivity	$\sigma_{\mathrm{EDM}} = \frac{\hbar}{2E} \frac{\epsilon}{\tau^{3/2} S}$ ϵ Noise density S Signal amplitude E E-field amplitude τ Coherence time	$\sigma_{\mathrm{EDM}} = \frac{\hbar}{2\alpha E \tau \sqrt{N}}$ α Visibility E E-field amplitude τ Coherence time N Number of neutrons detected	$\sigma_{\mathrm{EDM}} = \frac{\hbar}{2E\tau\sqrt{N}}$ E E-field amplitude τ Coherence time N Number of molecules detected	
Source	gas cylinder	turbine/ superfluid He/solid D2	cold (beam)	ultracold (trap)
Temperature	RT	3.5 mK	~K	<mK
Electric field	~10 kV/cm	~10 kV/cm	~10-**100 GV/cm**	
Coherence time	**~5000 s**	~100 s	~1 ms	~1 s
Number	>10^{16}*	~10^{4}	~10^{5}	~10^{3}-10^{4}

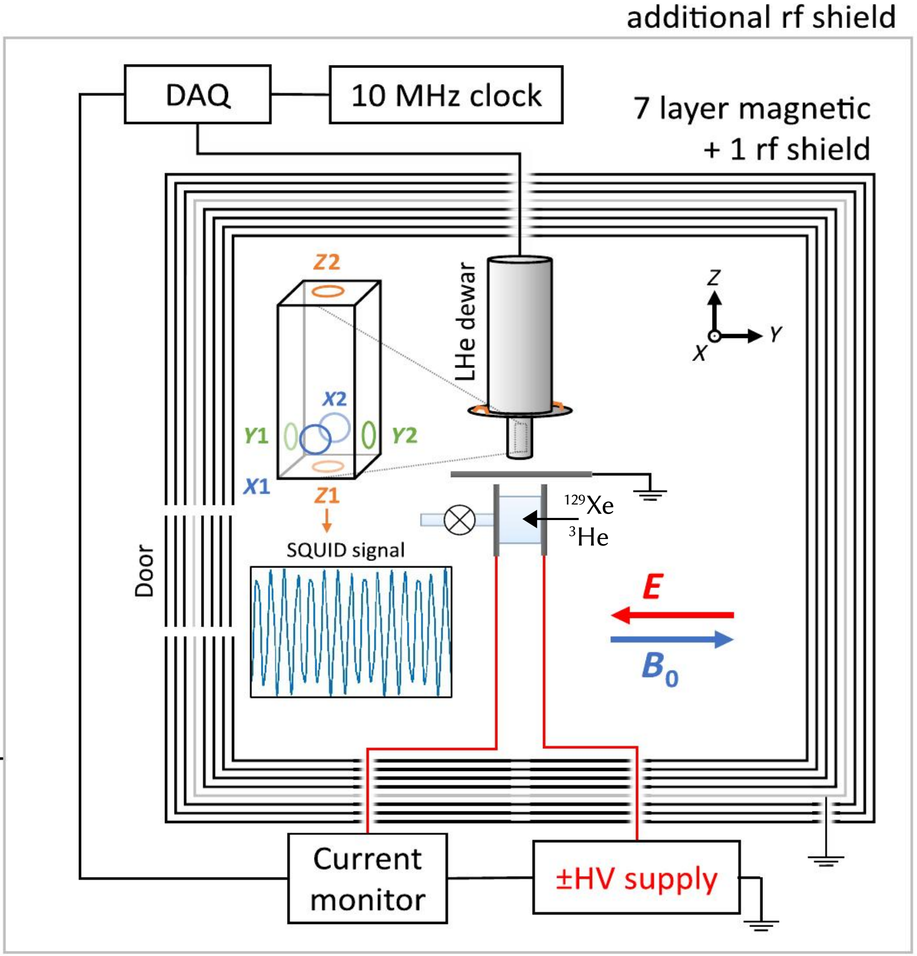
* external detection of precessing magnetization

HeXeEDM

New Limit on the Permanent Electric Dipole Moment of 129 Xe Using 3 He Comagnetometry and SQUID Detection

FK, Hyperfine Interact **237**, 95 (2016)
Sachdeva, Phys. Rev. Lett. **123**, 143003 (2019)
Terrano, Phys. Rev. A **100**, 012502 (2019)

HeXeEDM: Experimental setup



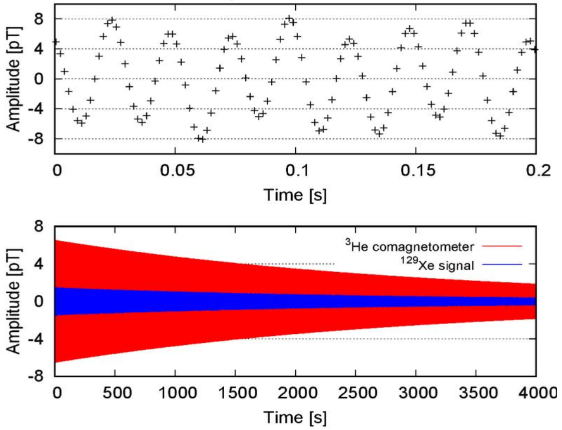
HeXeEDM setup at PTB Berlin

- ^{3}He comagnetometer cancels deviations in magnetic field in corrected frequency ω_d

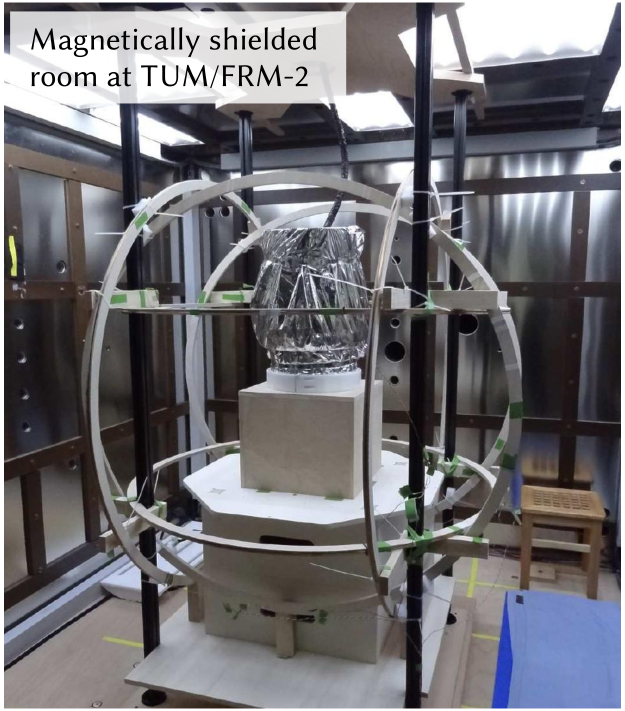
$$\omega_{\mathrm{d}} = \omega_{\mathrm{Xe}} - \frac{\gamma_{\mathrm{Xe}}}{\gamma_{\mathrm{He}}}\omega_{\mathrm{He}}$$

- High performance magnetical shield
- SQUID detection with noise < 10 fT/sqrt(Hz)
- HV up to +/-6 kV (2.7-3.2 kV/cm)
- T_2^* ~ 3700-8000 s for both species

Beat signal from ^{3}He and ^{129}Xe

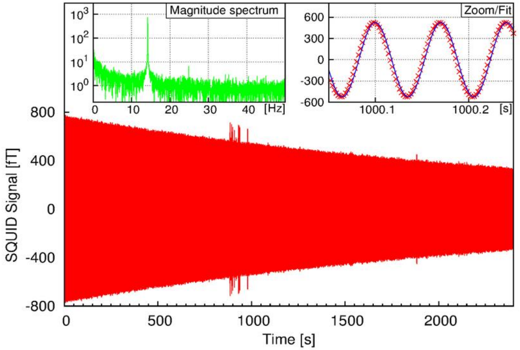


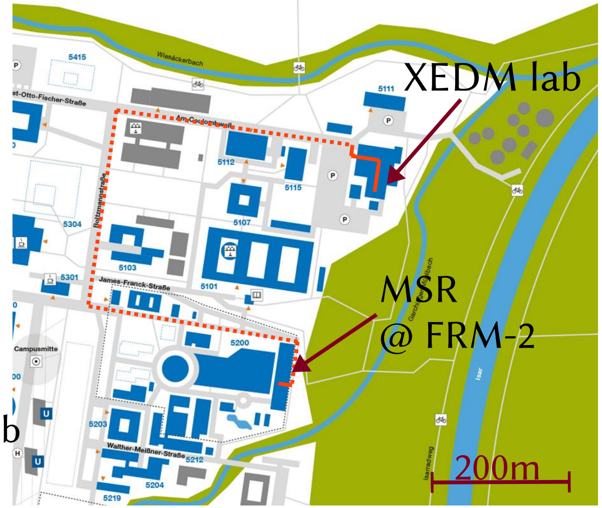
HeXeEDM at TU Munich/FRM-2



Altarev et al, Rev. Sci. Instr. 85, 075106 (2014)

|B| < 1 nT (10 μG)
|δB| < 0.3 nT/m (3 μG/m)
SF: 300 below 0.1 Hz
10^5 above 10 Hz



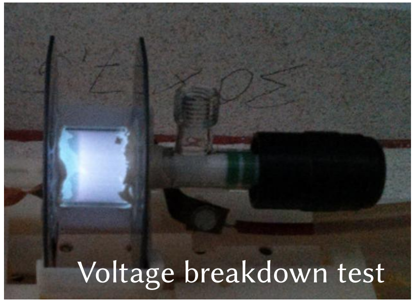


First precession signals!

- Polarized xenon from liquid xenon EDM lab across campus (~1 km drive)
- Polarized ^{3}He supply via elevator

Test runs and systematics studies:

- Electric field breakdown
- Simultaneous spin-exchange optical pumping of ^{129}Xe and ^{3}He (directly pumping Rb)
- Transport of polarized gas
- Interaction of highly polarized species

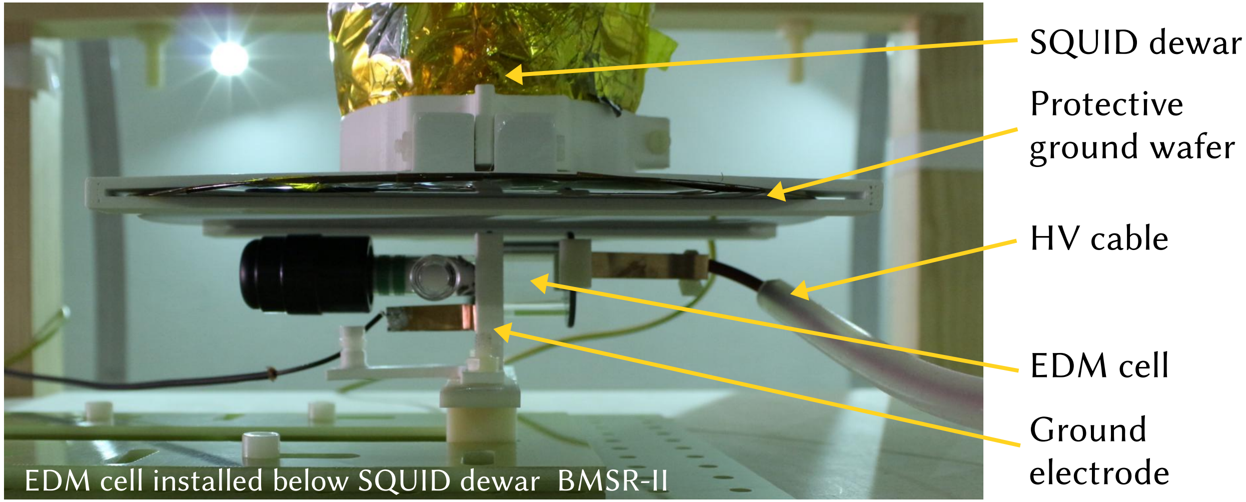


Students: Eva Kraegeloh, Jonas Meindl
Jakob Egge, Lorenz Emberger

HeXeEDM at PTB Berlin: Result and systematics

Munich MSR moved to ILL for PanEDM ⟶ EDM runs at PTB Berlin:

7 layer BMSR-II: |B| < 0.8 nT (8 μG)
|δB| < 0.4 nT/m (4 μG/m)
SF: 75000 below 0.1 Hz
10^8 above 6 Hz



EDM cell installed below SQUID dewar BMSR-II

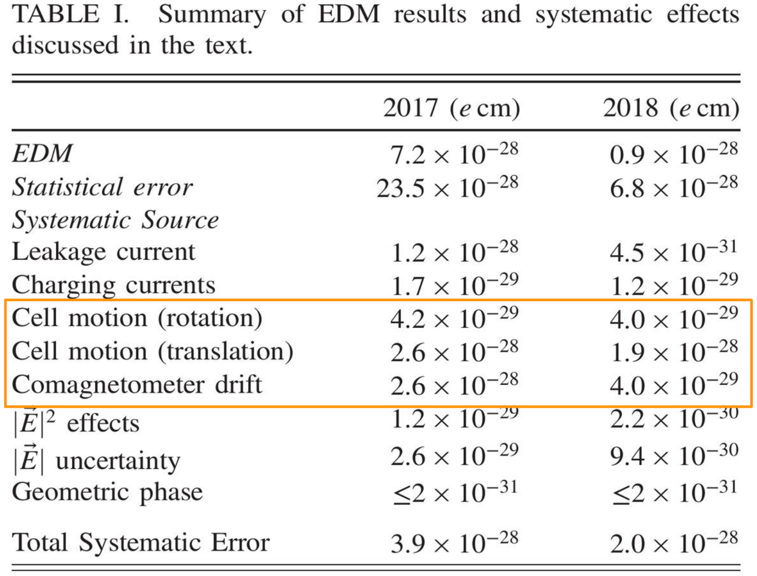


TABLE I. Summary of EDM results and systematic effects discussed in the text.

	2017 (*e* cm)	2018 (*e* cm)
EDM	7.2×10^{-28}	0.9×10^{-28}
Statistical error	23.5×10^{-28}	6.8×10^{-28}
Systematic Source		
Leakage current	1.2×10^{-28}	4.5×10^{-31}
Charging currents	1.7×10^{-29}	1.2×10^{-29}
Cell motion (rotation)	4.2×10^{-29}	4.0×10^{-29}
Cell motion (translation)	2.6×10^{-28}	1.9×10^{-28}
Comagnetometer drift	2.6×10^{-28}	4.0×10^{-29}
$\lvert\vec{E}\rvert^2$ effects	1.2×10^{-29}	2.2×10^{-30}
$\lvert\vec{E}\rvert$ uncertainty	2.6×10^{-29}	9.4×10^{-30}
Geometric phase	$\lesssim 2 \times 10^{-31}$	$\lesssim 2 \times 10^{-31}$
Total Systematic Error	3.9×10^{-28}	2.0×10^{-28}

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

Future improvements:

- Measurement time
- Cell motion
- Comagnetometer drift

Result from combined 2017/2018 data:
Improves previous limit by factor 5

$$|d_{\mathrm{Xe}}| \leq 1.4 \times 10^{-27}\ e\mathrm{cm} \quad (95\%\ \mathrm{C.L.})$$

⟶ improves constrains on CPV parameters $\bar{g}^{0,1}_{\pi}$ and C_T Chupp, Phys. Rev. C **91**, 035502 (2015)

HeXeEDM: Comagnetometer systematics

^{3}He comagnetometer largely cancels systematics, but needs corrections:

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

$$\omega_{\mathrm{co}} \approx \omega_{\mathrm{d}} \quad - \quad \gamma'_{\mathrm{He}}\Delta RB \quad + \quad (1-R)\vec{\Omega}.\hat{B} \quad + \quad \gamma'_{\mathrm{Xe}}(\Delta B^{\mathrm{dif}}_{\mathrm{Xe}} - \Delta B^{\mathrm{dif}}_{\mathrm{He}}) \quad + \quad (\omega^{\mathrm{sd}}_{\mathrm{Xe}} - R\omega^{\mathrm{sd}}_{\mathrm{He}})$$

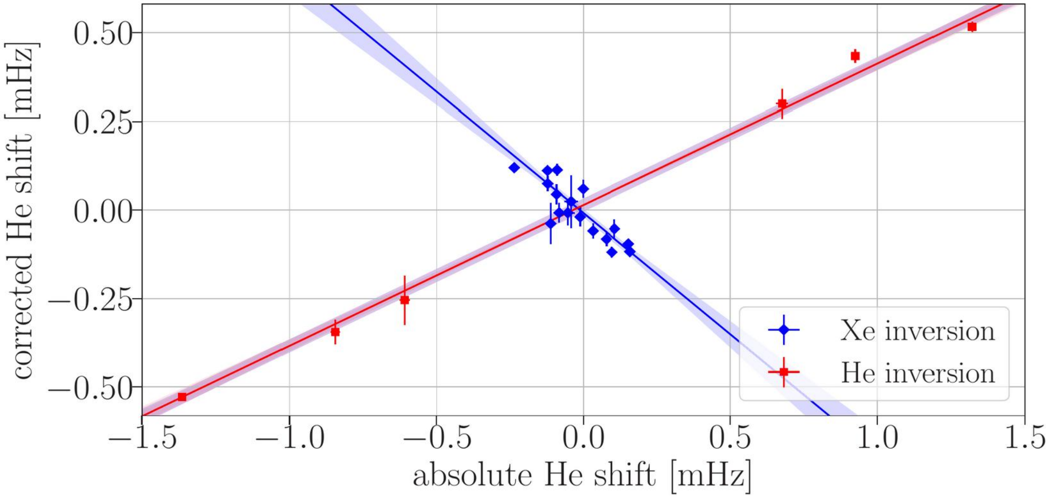
EDM contribution

pressure dependent chemical shifts

Earth's rotation

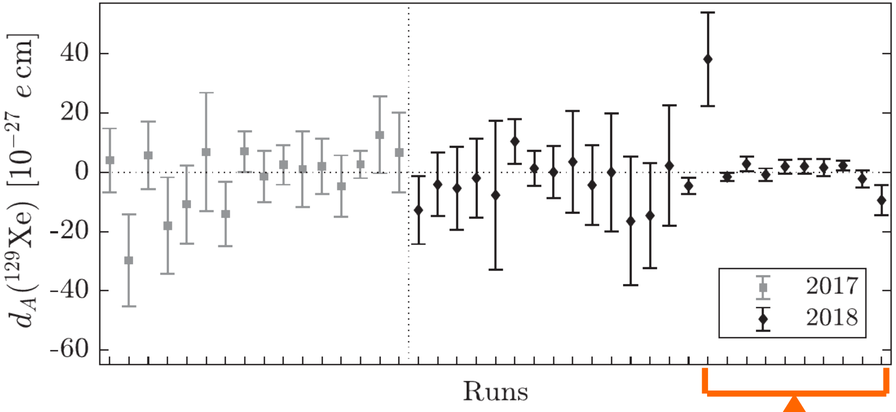
difference in volume avg magnetic field due to diffusion

Comagnetometer drifts due to residual longitudinal magnetization



= change in longitudinal magnetization

Terrano, Phys. Rev. A **100**, 012502 (2019)



Comagnetometer drift reduced by tuning:

- Magnetization ratio $M^{\mathrm{Xe}}/M^{\mathrm{He}}$
- Spin flip accuracy < 1°
- Cell geometry

Limes, Phys. Rev. A **100**, 010501 (2019)

TRIUMF KEK RCNP The University of Winnipeg

The University of British Columbia University of Manitoba SFU Simon Fraser University Engaging the World Nagoya University

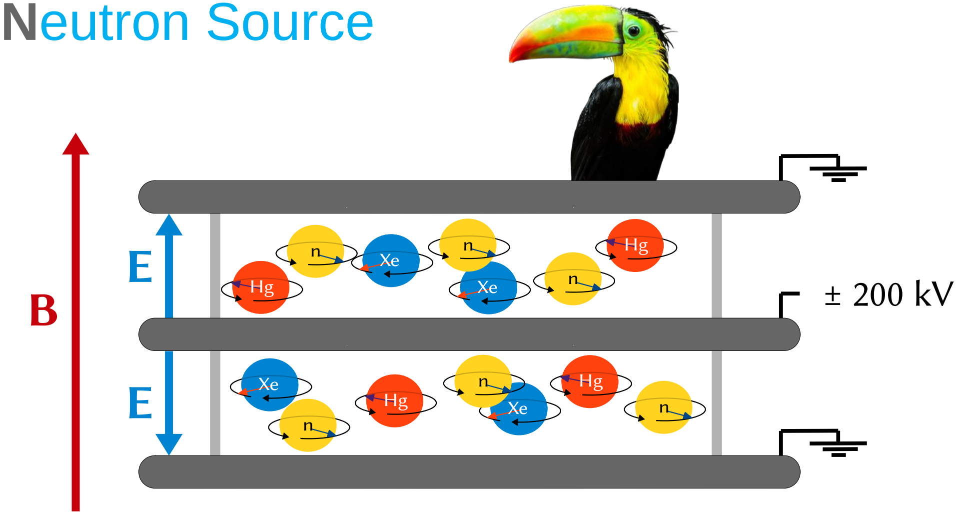
UNBC University of Northern British Columbia

TUCAN EDM

TRIUMF **U**ltra **C**old **A**dvanced **N**eutron Source

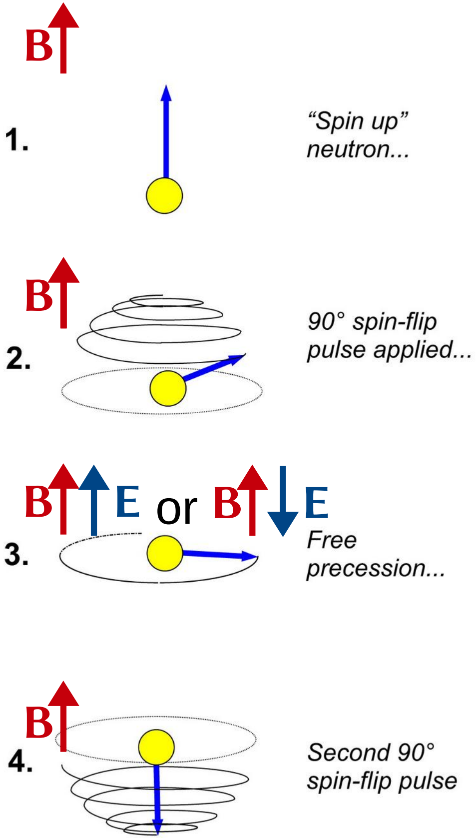
UCN project and TUCAN's goals

- Search for an electric dipole moment (EDM) of the neutron with a sensitivity below 10^{-27} ecm
- Build world-leading UCN source
- Establish UCN user facility



Neutron EDM current status

Worldwide: PSI, ILL/TUM, ILL/PNPI/Gatchina, LANL, SNS, TRIUMF



“Spin up” neutron...

90° spin-flip pulse applied...

Free precession...

Second 90° spin-flip pulse

$$\sigma_d = \frac{\hbar}{2\alpha ET\sqrt{N}}$$

α - Visibility (spin polarization, detection efficiency)
E - Electric field
T - Spin precession time
N - Number of UCN

2006 ILL result

$$|d_n| \leq 3.6 \times 10^{-26}\ e\mathrm{cm}$$

2020 PSI result

$$|d_n| \leq 1.8 \times 10^{-26}\ e\mathrm{cm}$$

		PSI 2016	ILL 2006
α		0.75	0.58
T	(s)	180	130
E	(kV/cm)	11	7
N		15 000	14 000
N_{cycles}	(cycles/day)	288	400
$\sigma(d_{\mathrm{n}}^{\mathrm{meas}})$	(e cm per day)	1.110^{-25}	2.610^{-25}

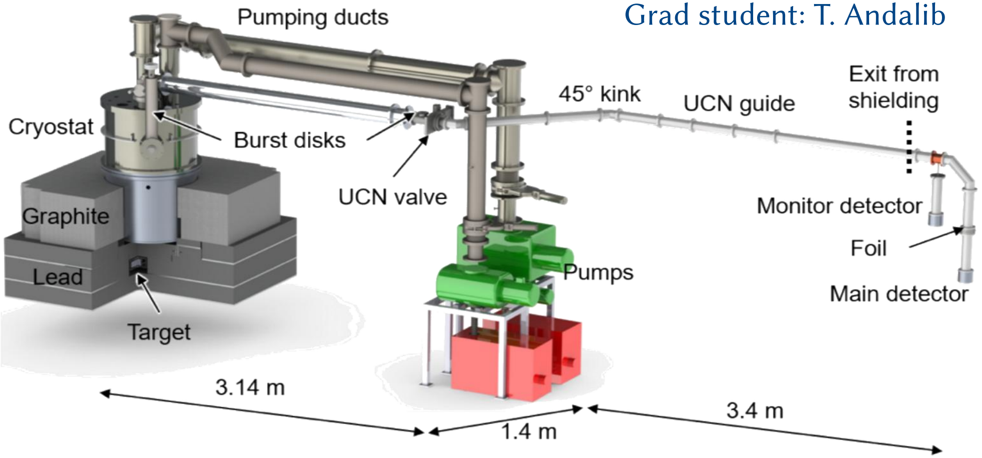
- Detailed understanding of magnetic field gradient → large correction (~60% of statistical error)
- Limitation for next generation: UCN density

Baker, Phys. Rev. Lett. 97, 131801 (2006)
Baker, Nucl. Intr. Meth. A 736, 184 (2014)
Abel, EPJ Web Conf. 219, 02001 (2019)
Abel, Pys. Rev. Lett. 124, 081803 (2020)

Accomplishments and plans of the TUCAN UCN project

Nov 2016	Beam on (UCN) target
Jan-Apr 2017	Installation of prototype UCN source
Nov 2017	First UCN produced
Fall 2018/2019	UCN runs testing equipment (UCN guides, polarized UCN, detectors)

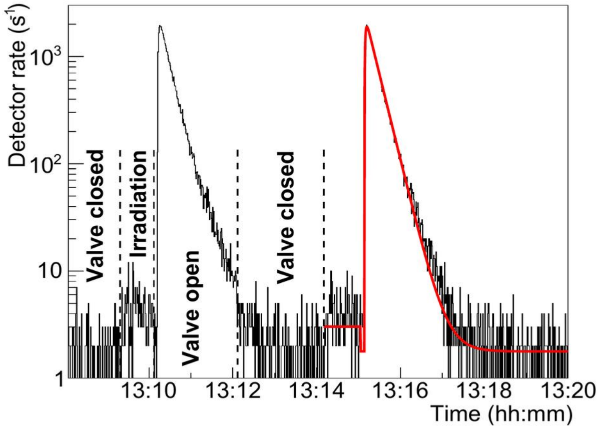
COOP students: S. Vanbergen, A. Ezzat, S. Morawetz
Grad student: T. Andalib

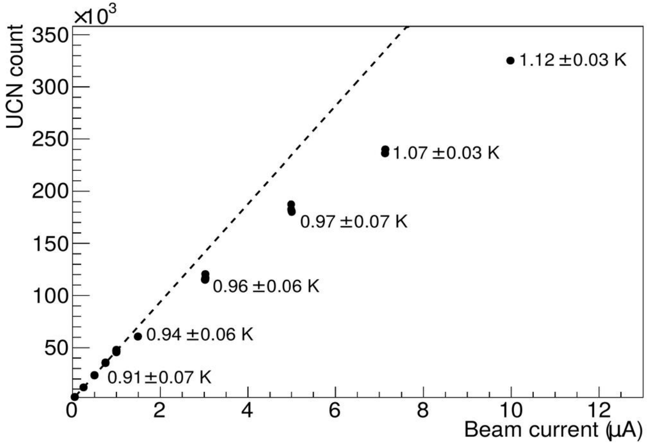


Ahmed (TUCAN collaboration), Phys. Rev. C **99**, 025503 (2019)
Ahmed (TUCAN collaboration), Nucl. Inst. Meth. A **927**, 101 (2019)
Ahmed (TUCAN collaboration), Phys Rev Accel Beams **22**, 102401 (2019)

Unique combination of spallation target/superfluid helium:

Spallation: free neutrons
~ 1 MeV 10^9 K
Moderation, reflection
~eV 300 K
Downscattering
300 neV 0.003 K





The new TUCAN Source

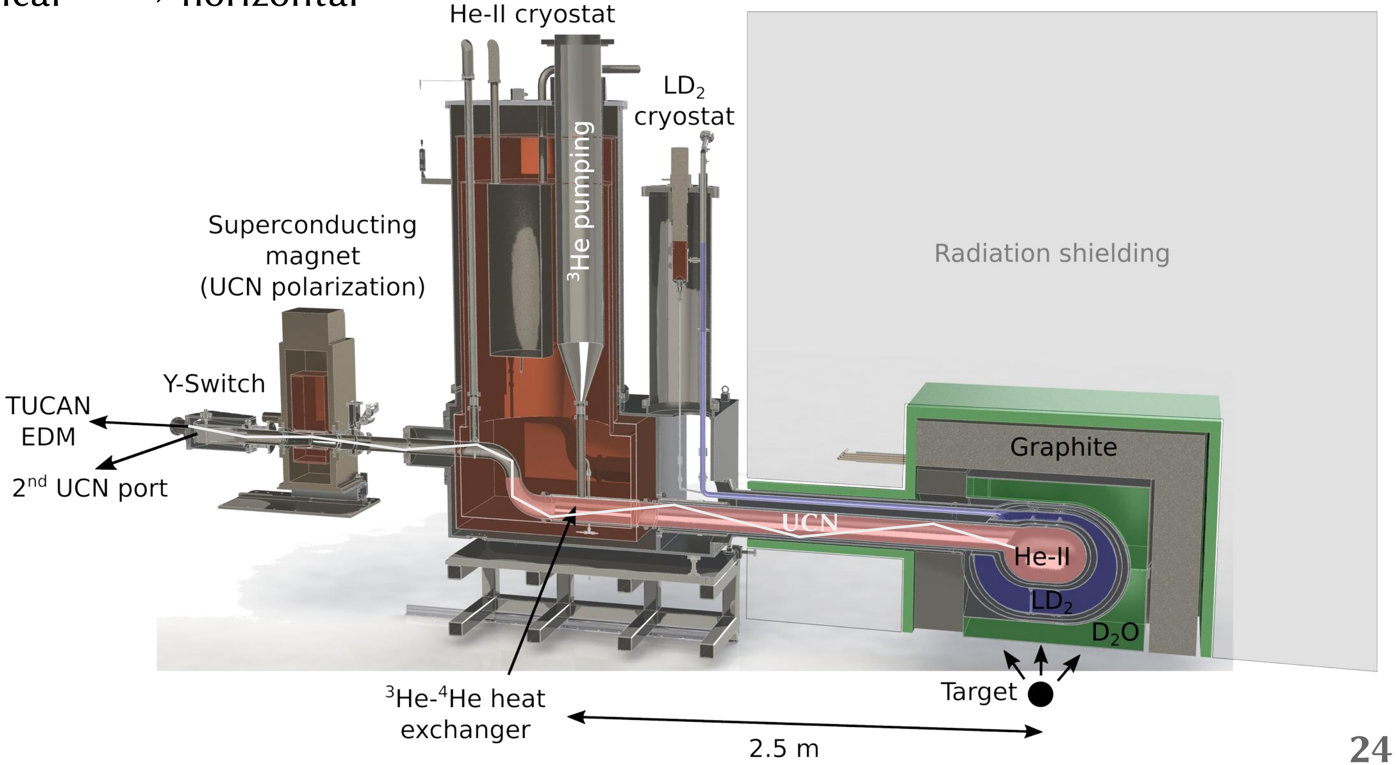
Cooling power (~1K)	0.3 W	→ 10 W
Beam current on target	1 μA	→ 40 μA
Cold moderator @20 K	sD2O	→ LD2
Superfluid UCN prod. volume	8 L	→ 34 L
UCN production rate	2x10^5 /s	→ 1.7x10^7/s
UCN extraction	vertical	→ horizontal

Schedule

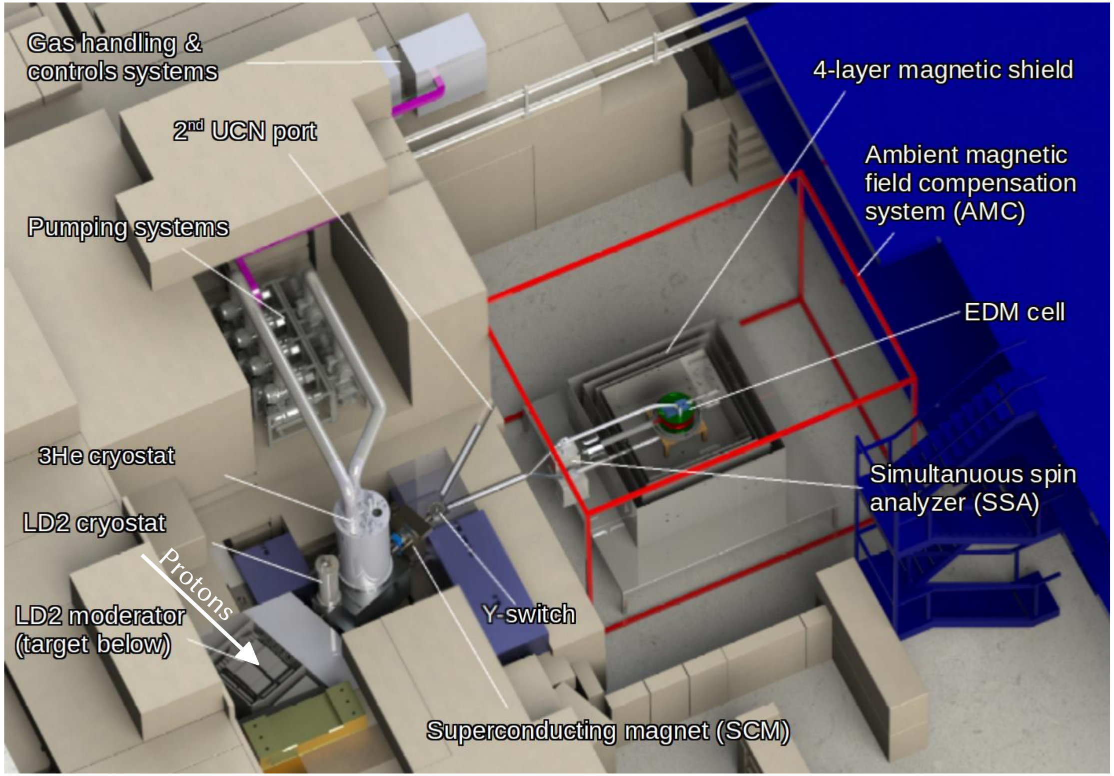
2020 ^{3}He cryostat manufacturing
and testing at KEK, Japan

2021 Start installation of new TUCAN Source


Manufacturing of ^{3}He cryostat



TUCAN EDM experiment at TRIUMF



Goal (2 yrs/400 beam days): $|d_n| \leq 10^{-27}$ $e\text{cm}$

Features:

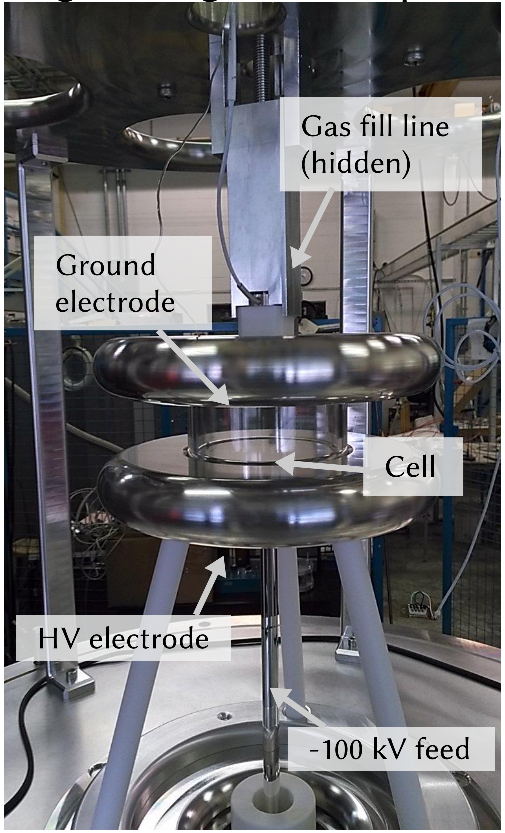
- Simulation (incl. EDM cycle optimization): ~ 2x10^6 UCN/cell
- Future dual comagnetometer (^{199}Hg/^{129}Xe):
  - Optical readout (two-photon transition)
    Altiere, Phys. Rev. A **97**, 012507 (2018)
  - Xenon breakdown strength
  - Xenon EDM $|d_{\mathrm{Xe}}| \lesssim 10^{-28}$ $e\text{cm}$

Dual comagnetometer adresses key systematic effect by determining magnetic field and magnetic field gradient (i=Xe,Hg)

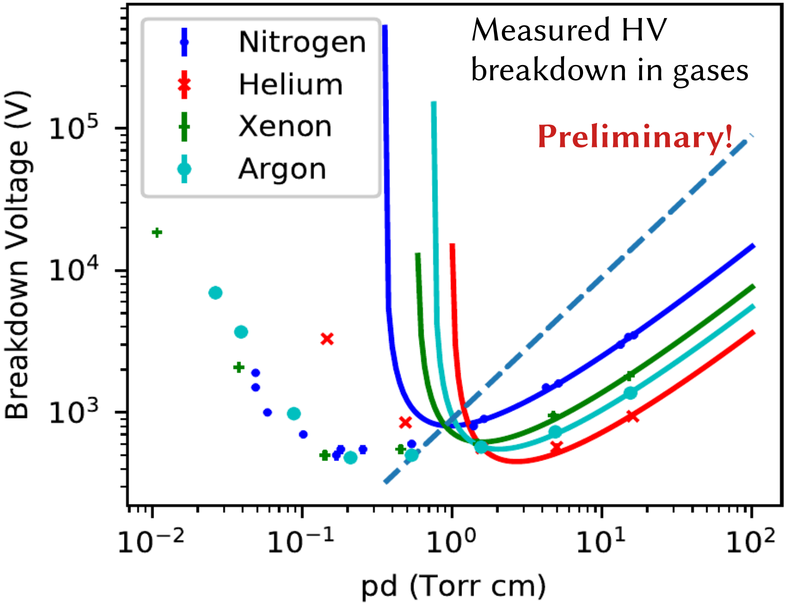
$$\omega_i^{\uparrow\uparrow} = \gamma_i B_0 - \underbrace{\frac{1}{4c^2}\gamma_i^2 R^2 \frac{\partial B_{0z}}{\partial z}|E|}_{\text{shift from geometric phase effect}}$$

TUCAN EDM: Storage cell and high-voltage development

High-voltage test setup



- Measure electric field breakdown in xenon
- High-voltage tests (up to 100 kV) of electrodes, insulator materials, coatings



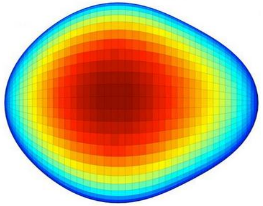
Coop/UBC students: D. Byer, B. Hong

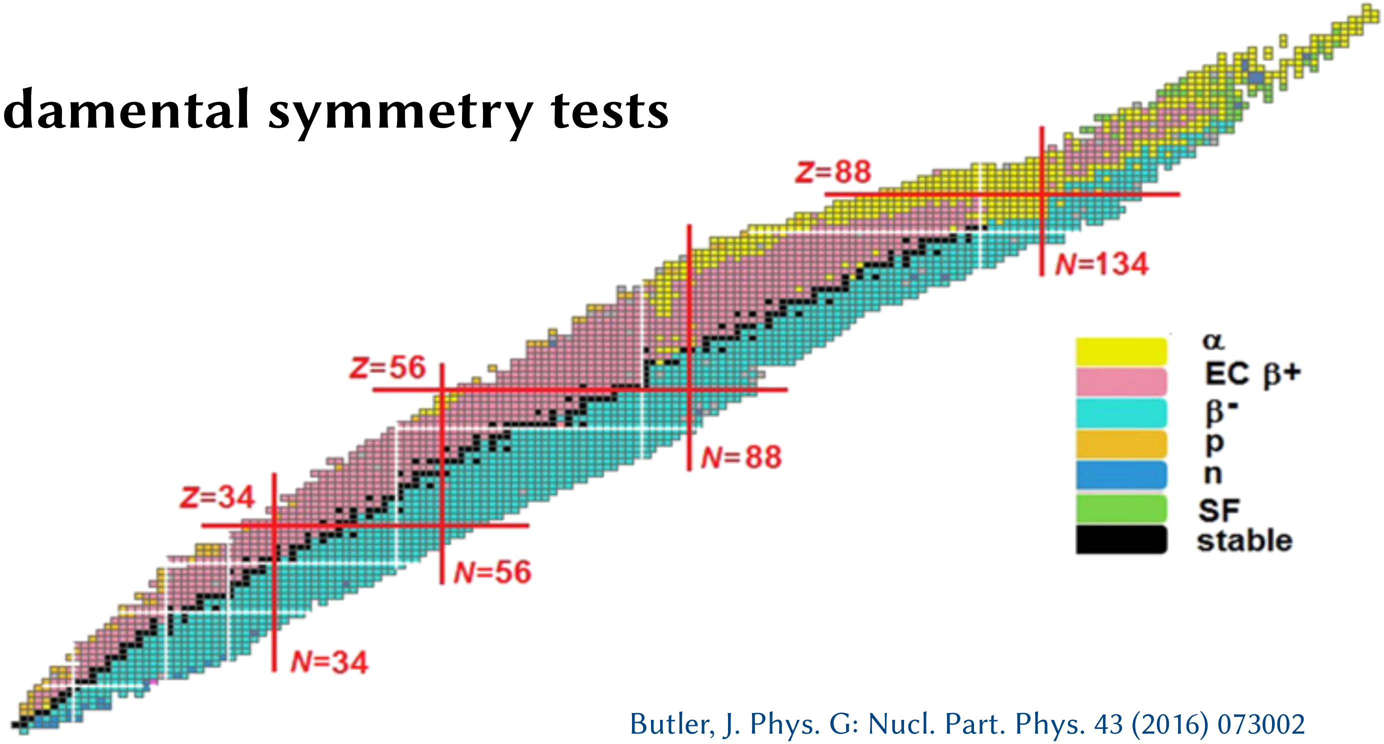
Optimization of the EDM cell:

- Coating materials and setup
  Coop student: S. Morawetz
- Electric field simulations
- Geometry
- UCN simulations and optimization of statistics
  Grad student: S. Sidhu

Rare isotopes and radioactive molecules

New directions for fundamental symmetry tests





Butler, J. Phys. G: Nucl. Part. Phys. 43 (2016) 073002

Octupole deformed nuclei

Enhancement of P,T odd effects in heavy, octupole deformed nuclei

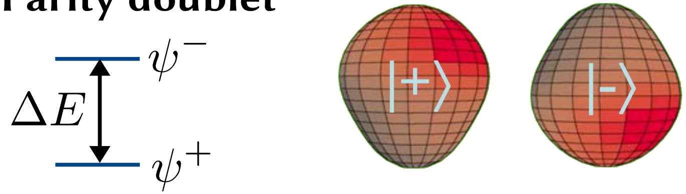
Schiff moment: $S \propto \beta_2 \beta_3^2 Z A^{2/3} \frac{1}{\Delta E}$

Quadrupole/octupole deformation parameters

Atomic number

Mass number

Parity doublet



$$\psi^\pm = (|+\rangle \pm |-\rangle)/\sqrt{2}$$

Parity violating interaction:

$$\psi = \psi^+ + \frac{\langle \psi^+ | V^{\mathrm{PT}} | \psi^- \rangle}{\Delta E} \psi^-$$

Enhancement of atomic EDM in octupole deformed nuclei vs spherical → factor 100~1000 Flambaum, Phys. Rev. A **65**, 032113 (2002)

Radium EDM experiment using atomic trap: $|d_{\mathrm{Ra}}| \lesssim 1.4 \times 10^{-23}\ e\mathrm{cm}$

- → Permanent octupole deformation
- → Enhanced sensitivity (x300) to Schiff moment vs spherical ^{199}Hg

Parker, Phys. Rev. Lett. **114**, 233002 (2015)
Bishof, Phys. Rev. C **94**, 025501 (2016)

Gaffney, Nature, **497**, 199-204 (2013)

Radium fluoride for electron EDM measurements

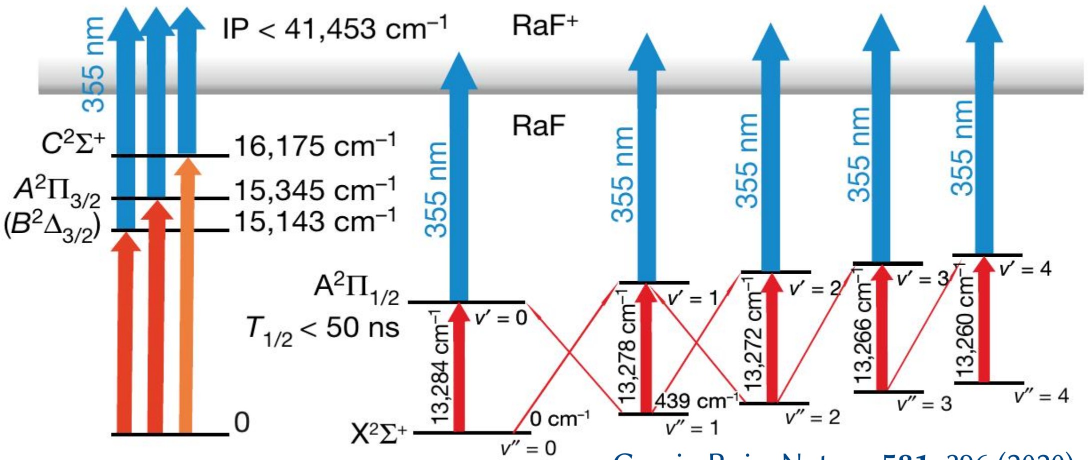
- Large effective electric field experienced by electrons **E_{eff} ~ 52 GV/cm**

  Isaev, Phys. Rev. A **82**, 052521 (2010)
  Kudashov, Phys. Rev. A **90**, 052513 (2014)
  Sasmal, Phys.R ev. A **93**, 062506 (2016)

- Spectroscopy data indicates possibility of laser cooling:
  - Short lifetime of excited state: 50ns
  - Small branching ratios to vibrational states (“dark”)

- TRIUMF/ISAC yields: $^{223\text{-}225}$Ra ~10^8-10^9 1/s
  http://isys01.triumf.ca/search/yield/data ^{223}Ra^{19}F ~10^6-10^7 1/s

- Systematic selection of radium nuclear spin



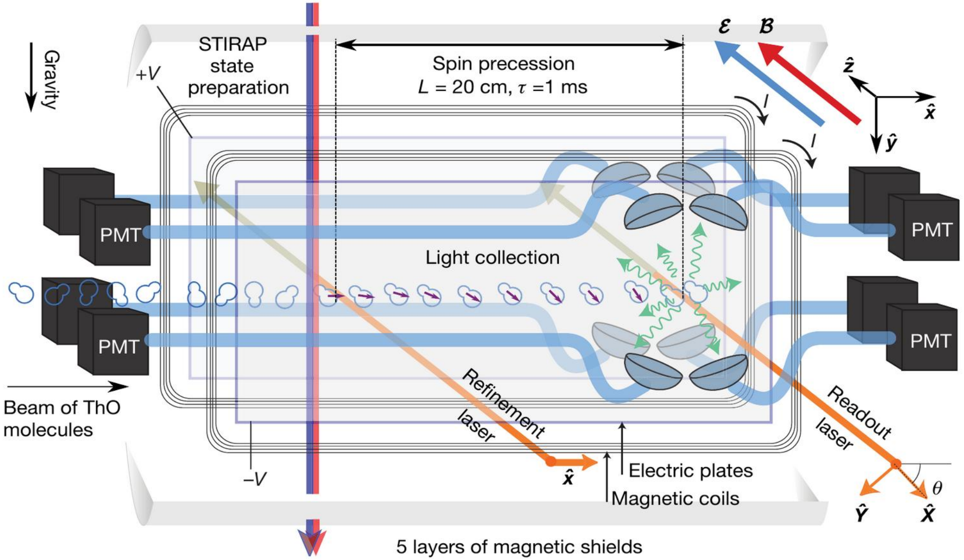
- Garcia Ruiz, Nature **581**, 396 (2020)

	^{223}Ra	^{224}Ra	^{225}Ra
Nuclear spin	3/2	0	1/2
Half life	11.43 d	3.66 d	14.90 d
ISAC avg yield [10^8/s]	1.7	9.6	1.0

Towards radioactive molecules: Electron EDM state of the art

Polar molecules widely used in electron EDM searches: $E_{\mathrm{eff}} \propto Z^3$

ACME electron EDM: ThO cold molecular beam



- Spin state prepared in plane perpendicular to E
- Phase ϕ accumulated in E_{eff} $\phi \approx \frac{-(\mu\tilde{\mathcal{B}}|\mathcal{B}_z| + \tilde{\mathcal{N}}\tilde{\mathcal{E}}d_e\mathcal{E}_{\mathrm{eff}})\tau}{\hbar}$
- Extensive systematics checks of >40 separate parameters

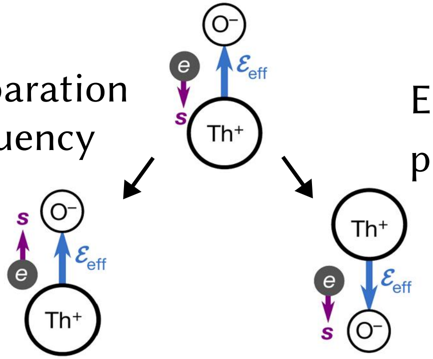
System	E_{eff} [GV/cm]	eEDM [$e$cm]	Ref
Tl	0.000123	< 1.6e-27	[1]
YbF	24-26	< 10.5e-28	[2]
HfF^+	22-24	< 1.2e-28	[3]
ThO	78-84	< 1.1e-29	[4]

[1] Regan, Phys. Rev. Lett. **88**, 071805 (2002)
[2] Hudson, Nature **473**, 493 (2011)
[3] Cairncross, Phys. Rev. Lett. **119**, 153001 (2017)
[4] ACME Collaboration, Nature **562**, 355 (2018)

Systematic d.E energy shift reversal:

state preparation laser frequency flips spin

E_{ext} field polarity



The path towards next generation electron EDM measurements

Enhancements scale with atomic number:

→ **Molecules with a heavy, deformed nucleus**

Fundamental sensitivity: $$\sigma_{\mathrm{EDM}} = \frac{\hbar}{2E\tau\sqrt{N}}$$

→ **Significantly higher sensitivity with improved coherence time**

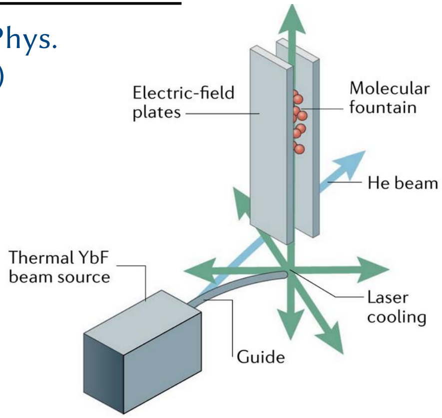
- HfF^{+} in ion trap: coherence time $\tau \sim 0.7$ s
  → compensates small number of detected ions (~10)
- Laser cooling and trapping: $\tau > 1$ s
  - Several molecules have been cooled and trapped

SrF	3.5 mK	Barry, Nature 512 286 (2014)
	400 uK (MOT)	Norrgard, Phys. Rev. Lett. 116, 063004 (2016)
CaF	340 uK (MOT)	Anderegg, Phys. Rev. Lett. 119, 103201 (2017)
	50 uK	Truppe, Nat. Phys. 13, 1173 (2017)
	5 uK	Caldwell, Phys. Rev. Lett. 123, 033202 (2019)
YO	4 mK (MOT)	Collopy. Phys. Rev. Lett. 121, 213201 (2018)
	4 uK	Ding, Phys. Rev. X 10, 021049 (2020)
YbF	100uK	Lim, Phys. Rev. Lett. 120, 123201 (2018)

New measurement techniques

YbF molecular fountain

Tarbutt, New J. Phys. **15**, 053034 (2013)



Polyatomic molecules:

→ PolyEDM (eEDM in YbOH)

- laser-coolable
- internal comagnetometer states

Kozyryev, Phys. Rev. Lett. **119**, 133002 (2017)
Augenbraun, New J. Phys. **22**, 022003 (2020)

Summary

EDM searches

- Valuable results hunting for signs of new physics
- Employ atomic, nuclear, particle physics techniques
- Systematics need to be well understood

Science opportunities with rare isotopes and radioactive molecules at ISAC

➔ Highest sensitivity to P,T odd effects in heavy, deformed nuclei
(also as as part of radioactive molecules)

➔ High electric fields E_{eff} in heavy polar molecules → sensitivity to electron EDM

➔ Prospects of laser cooling and trapping → long coherence times

➔ Projected energy reach into PeV region for next generation of electron EDM measurements
Cairncross, Nat. Rev. Phys. **1**, 510 (2019)

Thank you!

(A selection of) EDM searches in various systems

System		Experiments	Status [ecm]	SM pred. [ecm]	Reference
Neutron	Particle	PSI, ILL/TUM, ILL/PNPI/ Gatchina, LANL, SNS, TRIUMF	1.8x10^{-26}	10^{-31} - 10^{-33}	[1, 2]
Mercury	Diamagnetic atoms	UW	7.4x10^{-30}	10^{-34} - 10^{-35}	[3, 4]
Xenon		TUM/PTB Mainz/Heidelberg, Japan	1.4x10^{-27}	10^{-32} - 10^{-36}	[5, 6, 7]
Radium		Argonne	1.4x10^{-23}	-	[8]
ThO	Polar molecule	Harvard/Yale	1.1x10^{-29}	$<10^{-38}$	[9, 10]

Experiments

[1] Abel, Phys. Rev. Lett. **124**, 081803 (2020)
[3] Graner, Phys. Rev. Lett. **116**, 161601 (2016)
[5] Sachdeva, Phys. Rev. Lett. **123**, 143003 (2019)
[6] Allmendinger, Phys. Rev. A **100**, 022505 (2019)
[8] Bishof, Phys. Rev. C **94**, 025501 (2016)
[10] ACME Collaboration, Nature **562**, 355 (2018)

Theory

[2] Ellis, Nucl. Instr. Meth. A **284**, 33 (1989)
[4] Donoghue, Phys. Lett. B **196**, 196 (1987)
[7] Shushkov, Sov. Phys. JETP **60**, 873 (1984)
[9] Ng, Mod. Phys. Lett. A **11**, 211 (1996a)

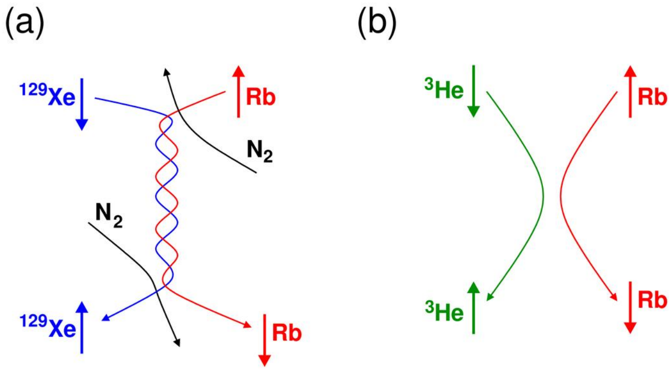
Particles
- Proton (CeNTREX)
- Muon

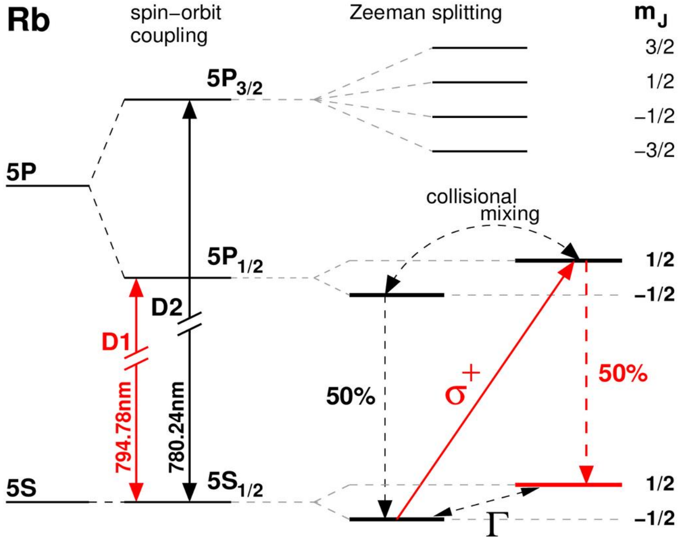
Atoms
- Paramagnetic
    - Cesium
    - Thallium
    - Francium
- Diamagnetic
    - Radon

Polar molecules
- TlF
- YbF
- HfF+
- PbF
- PbO
- HgF
- …

Spin-Exchange Optical Pumping

- Circularly polarized light is selectively de-populating alkali metal electron state
- Spin polarization transferred to noble gas nuclei during collisions (spin-exchange)
- Two different processes:
  (a) van-der-Waals molecules
  (b) binary collisions





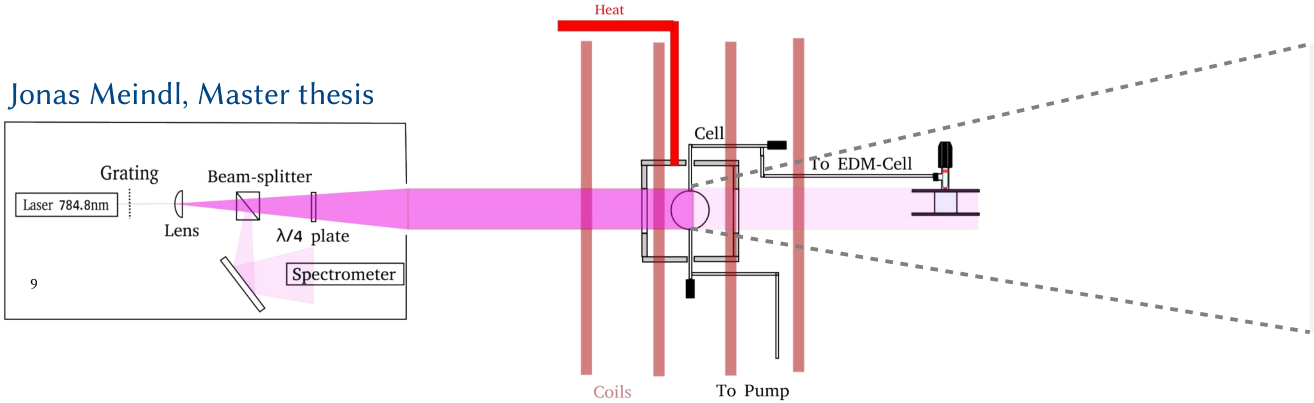
Spin-exchange rate:

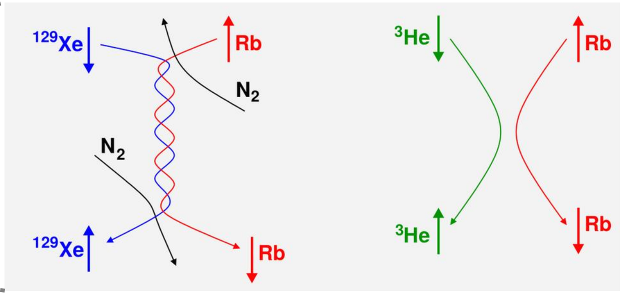
$$\gamma^{\mathrm{SE}} = \left(\sum_i \frac{\zeta_i}{[G_i]} + \sigma\bar{v}\right)[Rb]$$

	Rb		K	
Spin-exchange rates s^{-1}				
$k_{\text{He-Alk}}$	$6.8 \times 10^{-20}[\mathrm{Rb}]$	[86]	$5.5 \times 10^{-20}[\mathrm{K}]$	[86]
$k_{\text{Xe-Alk}}$	$1.0 \times 10^{-15}[\mathrm{Rb}]$	[87]	$6.3 \times 10^{-17}[\mathrm{K}]$	[87]
Spin-destruction rates ($T = 140\,^\circ\mathrm{C}$) s^{-1}				
$\Gamma_{\text{Alk-He}}$	$1.4 \times 10^{-18}[\mathrm{He}]$	[86]	$1.4 \times 10^{-19}[\mathrm{He}]$	[86]
$\Gamma_{\text{Alk-Xe}}$	$3.7 \times 10^{-16}[\mathrm{Xe}]$	[88]		

Spin-exchange optical pumping of ^{3}He and ^{129}Xe

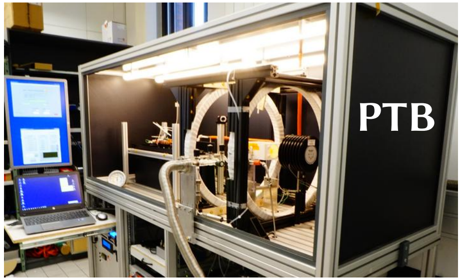
Jonas Meindl, Master thesis

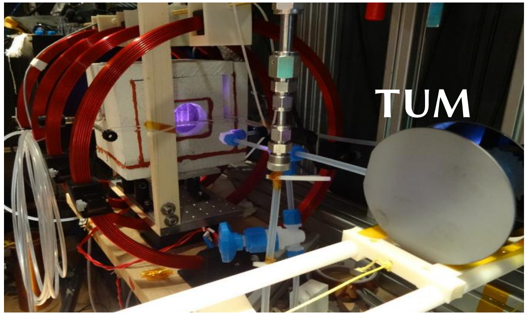




Walker et al, Rev. Mod. Phys. 69, 629 (1997)
Gentile et al, Rev. Mod. Phys. 89, 045004 (2017)

Laser:	100 W diode array 794.8 nm (water-cooled) width ~0.4 nm (narrowed by VBG)
Holding field:	B_0 ~ 3 mT
Oven:	>140 °C for ^{3}He (~ hrs) ~80 °C for ^{129}Xe (~ mins)
OP cells:	GE180 sealed bulbs GE180 with two Pyrex valves (TUM) Pyrex with one valve (PTB)
Location:	back of the MSR (TUM) one floor below the BMSR-II (PTB)
Polarization:	9-12% ^{129}Xe; 0.1-0.2% ^{3}He (PTB) (EDM cell with 0.5-1.0 bar)





Valved optical pumping cell
S. Degenkolb, T. Chupp

Magnetically shielded rooms

Magnetically shielded room @TUM

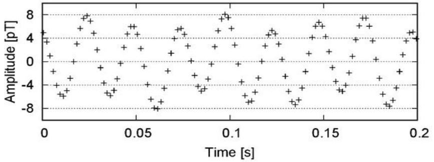
$|B| < 1$ nT (10 µG) $|\delta B| < 0.3$ nT/m (3 µG/m)

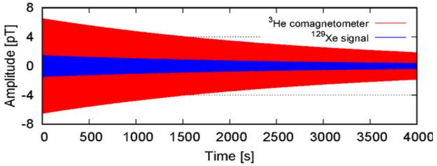
SF: 300 below 0.1 Hz 10^5 above 10 Hz

- techniques developed in test runs 2014-2016
- moved to ILL for PanEDM

Altarev et al, Rev. Sci. Instr. 85, 075106 (2014)

FK et al, Hyperfine Interact 237, 95 (2016)





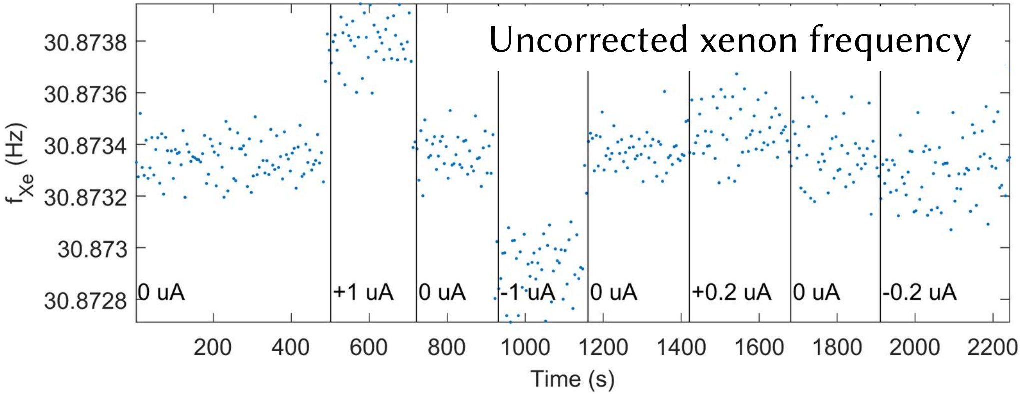
BMSR-II @PTB

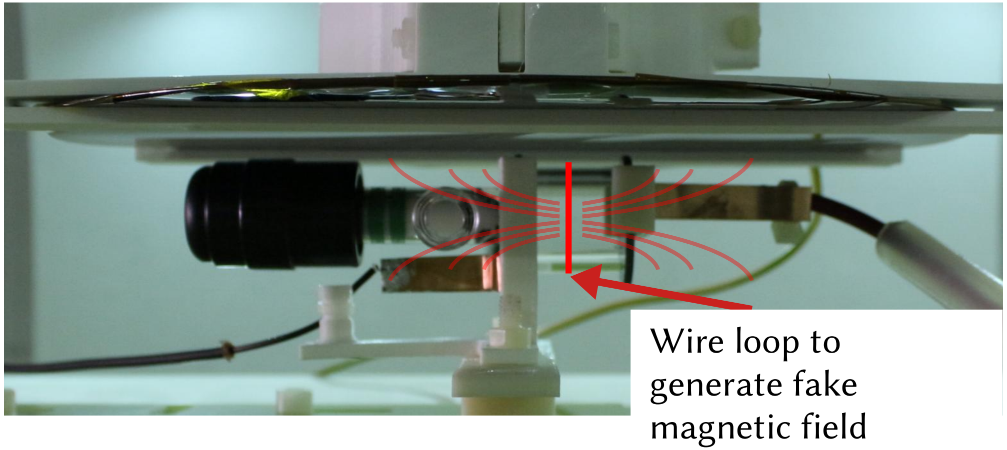
$|B| < 0.8$ nT (8 µG) $|\delta B| < 0.4$ nT/m (4 µG/m)

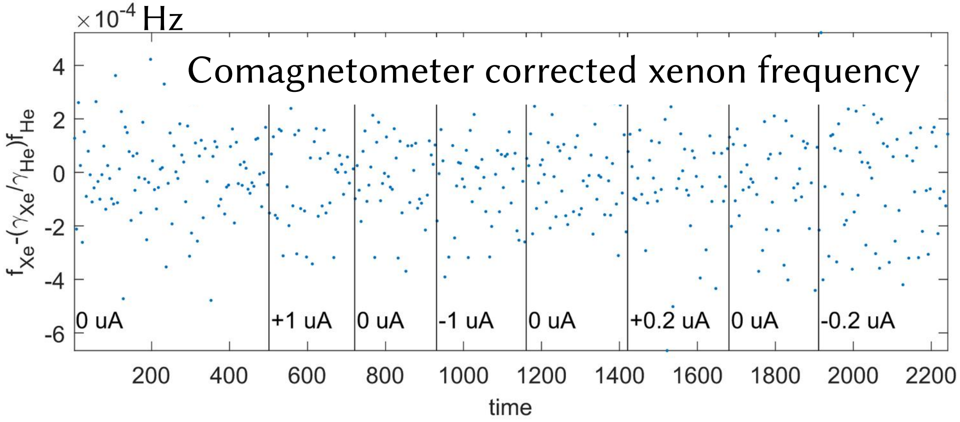
SF: 75000 below 0.1 Hz 10^8 above 6 Hz

- EDM runs in 2017, 2018

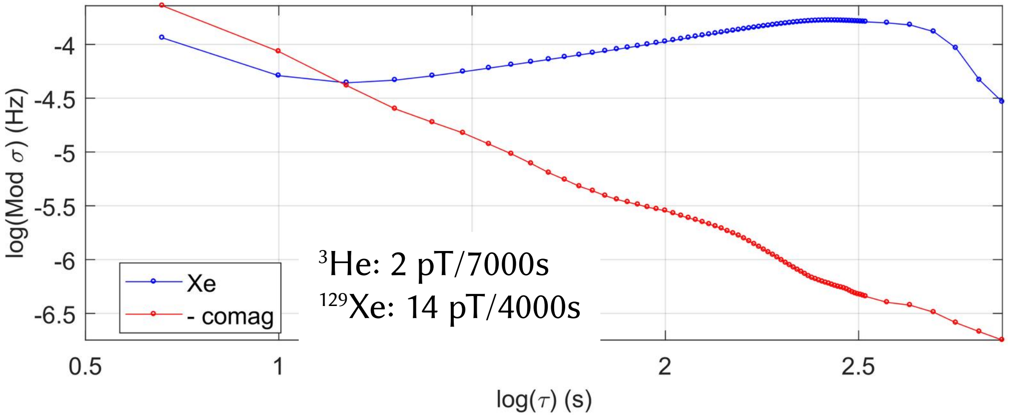
Bork et al, Proc. Biomag 2000, 970 (2000)




Wire loop to generate fake magnetic field



Allan deviation: uncorrected and corrected xenon frequency



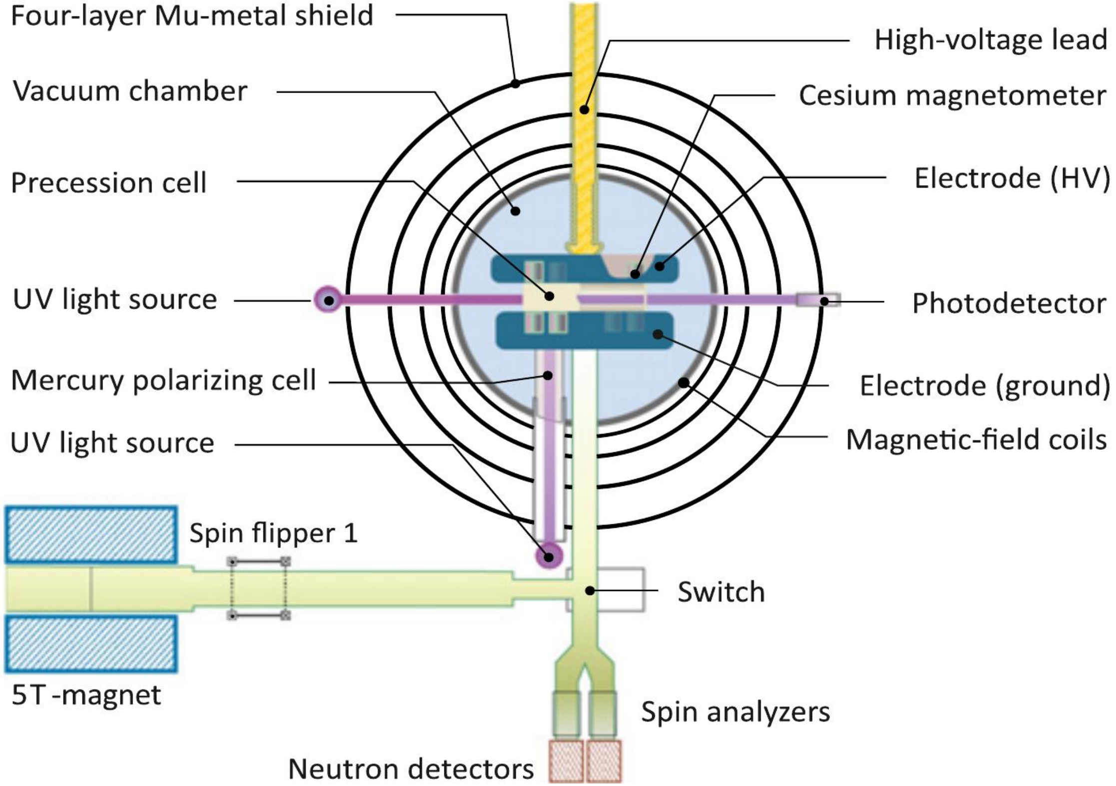
^{3}He: 2 pT/7000s

^{129}Xe: 14 pT/4000s

1 μA generated ~5 μHz shift for corrected xenon frequency

→ leakage current of 100 pA, eg. 0.5 nHz shift

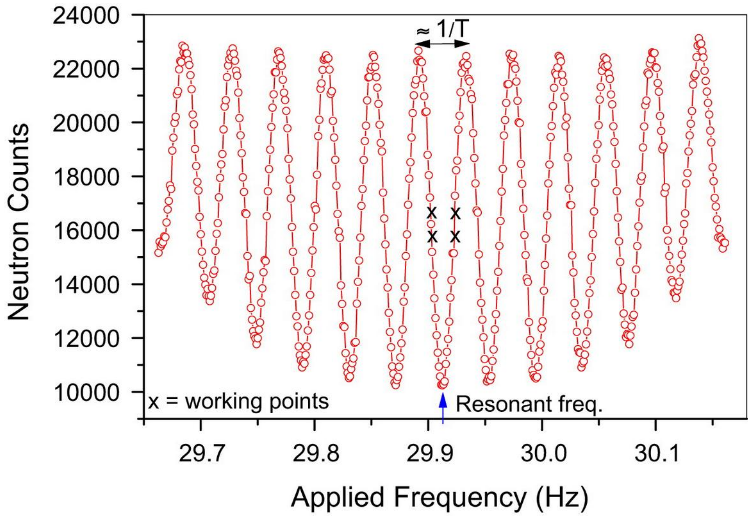
Neutron EDM experiment at PSI



Used upgraded setup of RAL-Sussex-ILL experiment

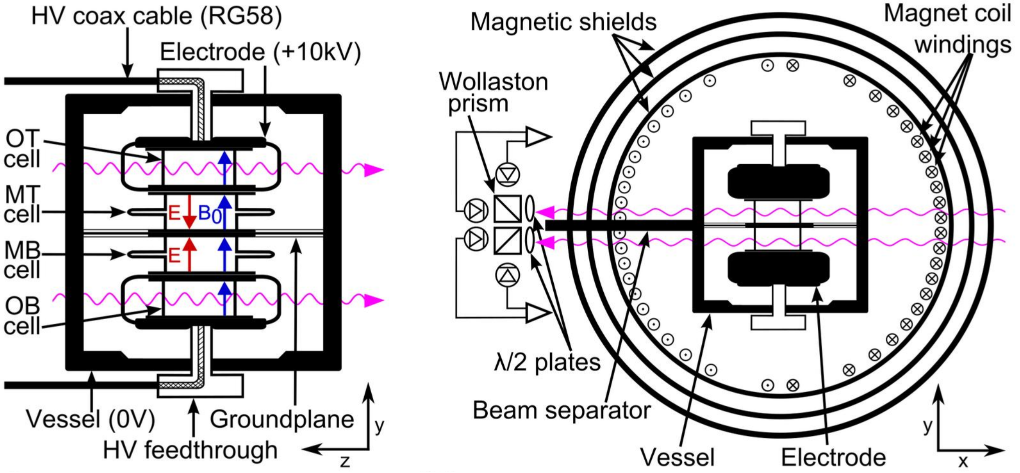
Electric field: 132 kV/12cm
(15 kV/cm possible but not with Cs magnetometers running)

Detector efficiency improvement ~18%

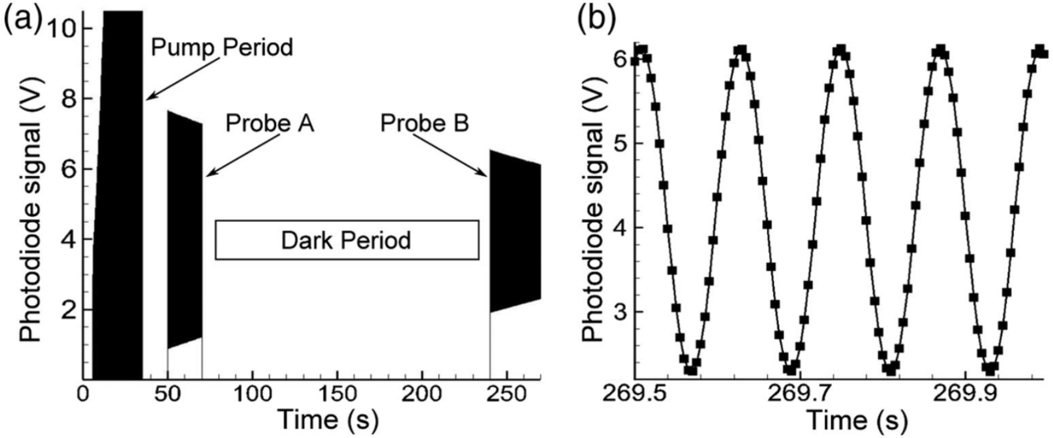


Mercury EDM experiment

- Four cells: two E=0, two E=±10 kV
- Transverse optical pumping of ${}^1S_0$(F=1/2) to ${}^3P_1$(F=1/2) transition (nuclear polarization)
- Optical detection: Faraday rotation of linearly polarized light (b=**B**.**k**)
- Determine phase difference accumulated in dark period (typ. 170s)



Graner, PRL **116**, 161601 (2017)



<u>Main systematic effects:</u>

- nm movements of cells in magnetic field gradients
- leakage current

Result $d_{Hg} < 7.4x10^{-30}$ ecm

<u>Note:</u> Constrains the neutron EDM to 1.6x10^{-26} ecm!

EDM experiment using trapped ^{225}Ra

Schiff moment: $S \propto \beta_2 \beta_3^2 Z A^{2/3} \frac{1}{\Delta E}$

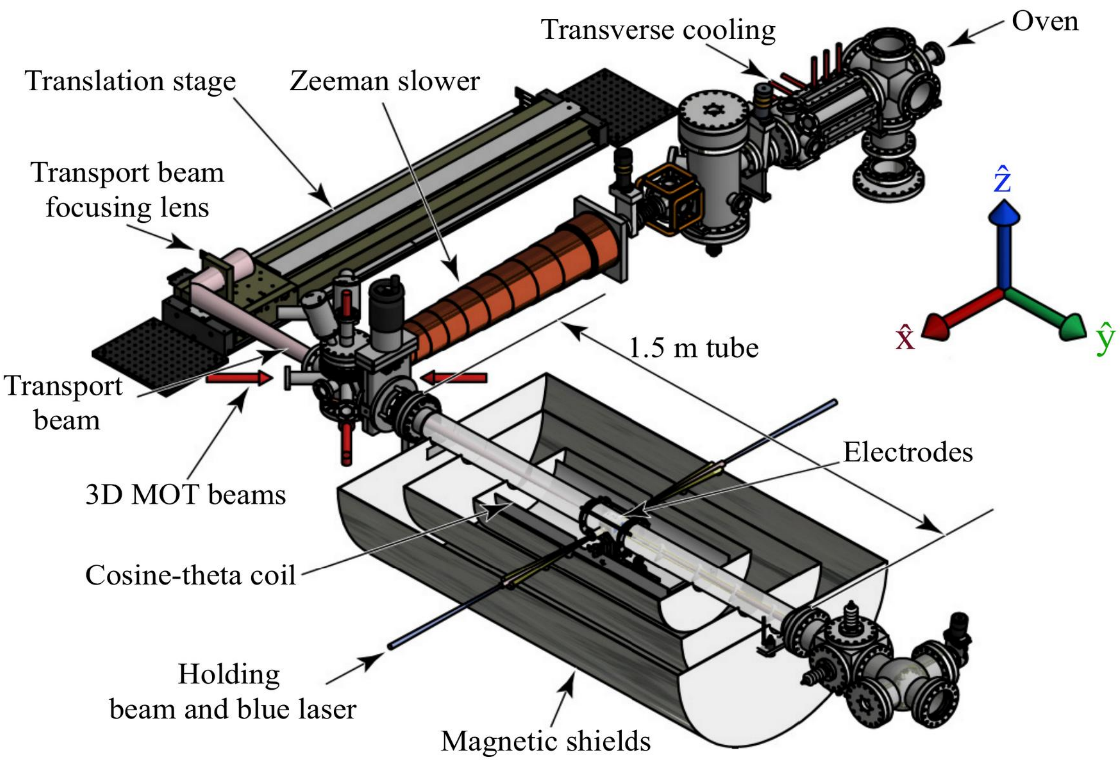
^{225}Ra properties:

Z=88
β_2=0.129, β_3=0.099
ΔE=55.2 keV

^{225}Ra from oven (~10^{10}) cooled, slowed, trapped (~10^4) and transferred by ODT (~10^3)

Result: $|d_{\mathrm{Ra}}| \lesssim 1.4 \times 10^{-23}\ e\mathrm{cm}$

Note: ^{225}Ra is ~300 times more sensitive to Schiff moment than (spherical) ^{199}Hg



Parker, Phys. Rev. Lett. **114**, 233002 (2015)
Bishof, Phys. Rev. C **94**, 025501 (2016)

Testing fundamental symmetries with rare isotopes

Parity doublet energy difference →

Schiff moment →

	^{223}Ra	^{225}Ra	^{223}Rn	^{221}Fr	^{223}Fr	^{225}Ac	^{229}Pa	^{199}Hg	^{129}Xe
ΔE_{expt} (keV)	50.2	55.2		234	160.5	40.1	0.22		
$S_{\text{intr}}(e\ \text{fm}^3)$	24	24	15	21	20	28	25		
$S(10^8\ \eta e\ \text{fm}^3)$	400	300	1000	43	500	900	1.2×10^4	-1.4	1.75
$d(\text{at})\ (10^{25}\ \eta e\ \text{cm})$	2700	2100	2000	240	2800			5.6	0.47

Reproduced from: Spevak, Phys. Rev. C **56**, 1357 (1997)

^{229}Pa: predicted to have very small ΔE<1 keV Singh, arXiv:1903.03206 (2019)

^{227}Ac (similar to deformed ^{226}Ra) with ΔE~27 keV I=3/2 (⟶ MQM)
highly available and ~22 yrs halflife Flambaum, Phys. Rev. C **101**, 015502 (2020)

^{223}Rn has no permanent octupole and close-lying parity doublets unlikely
Butler, Nat. Comm. **10**, 2473 (2019)

⟶ Radium is favorable for EDM experiments
Gaffney, Nature, **497**, 199-204 (2013)