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New measurement of the neutron electric dipole moment

Benoit Clément (on behalf of the nEDM collaboration)

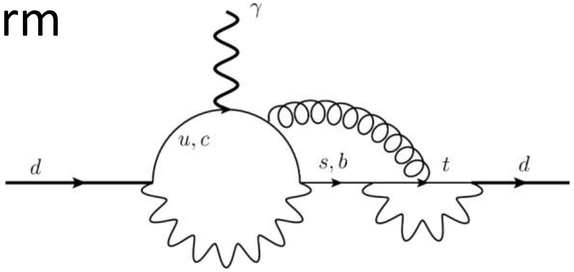
ICHEP 2020

Electric dipole moments

For the theoritician : CP-violating term

…in the EM current : $\mathcal{L}_{int} = \boldsymbol{i}\frac{d}{2}\bar{\psi}F_{\mu\nu}\sigma^{\mu\nu}\boldsymbol{\gamma^5}\psi$

Important for Baryon asymmetry !



In standard model, only through 3 (quarks) or 4 (leptons) loops EW diagrams

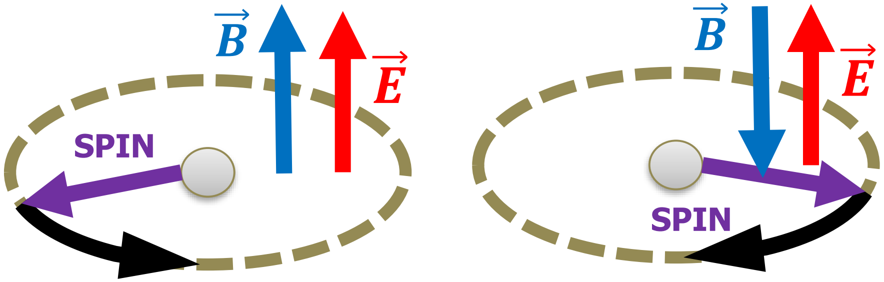
$$\Rightarrow\ d_n \approx\ 10^{-31} e.cm$$

BSM could contribute through lower order loops : $d_n \sim\ 10^{-29}$ to$10^{-26} e.$cm

For the experimentalist : T-violating effect

At low energy (non relativistic limit): $\mathcal{L}_{int} = -\vec{\boldsymbol{d}}.\vec{\boldsymbol{E}} = \boldsymbol{d}\vec{\hat{J}}.\vec{\boldsymbol{E}}$

Coupling between the **Spin** and an external **Electric Field**



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$\mu|B| \gg d|E|$

Change in Larmor frequency if B and E fields are (anti)parallel

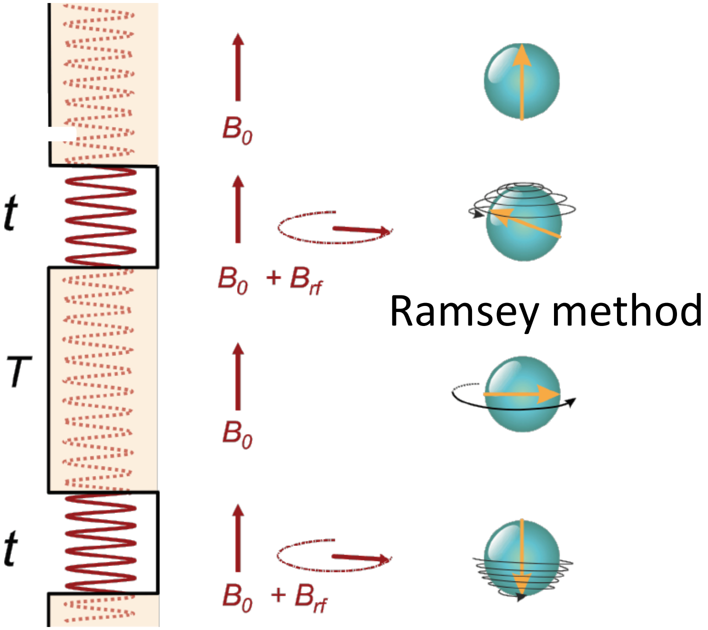
$$2\pi f = \frac{2\mu}{\hbar}|B| \pm \frac{2d}{\hbar}|E|$$

$$f(\uparrow\uparrow) - f(\uparrow\downarrow) = -\frac{2}{\pi\hbar}d|E|$$

$d_n < 3 \times 10^{-26}$ e.cm @ 90% CL

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

How to measure nEDM

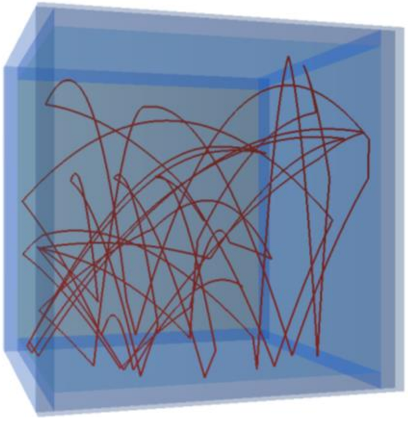


Ramsey method

Count neutrons in ↑ and ↓ spin states
Relate **asymmetry** to **precession frequency**

Statistical sensitivity: $\sigma_{d_n} = \dfrac{\hbar}{2\,\alpha\,E\,\boldsymbol{T}\sqrt{\boldsymbol{N}}}$

1 cycle : $T \approx 180s, N = 5000$ to 15000



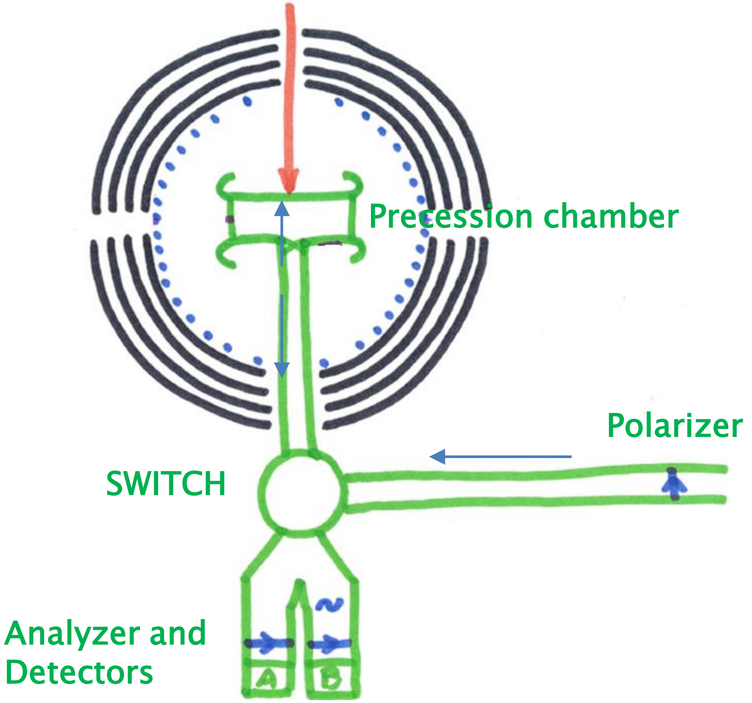
Ultracold neutrons :

- $E_{kin} \sim 100\mathrm{neV}, v \sim 4\mathrm{m.s}^{-1}$
- Reflected at all incidences
- Sensitive to gravity

Can be :

- guided through simple tubes
- stored in material « bottle »

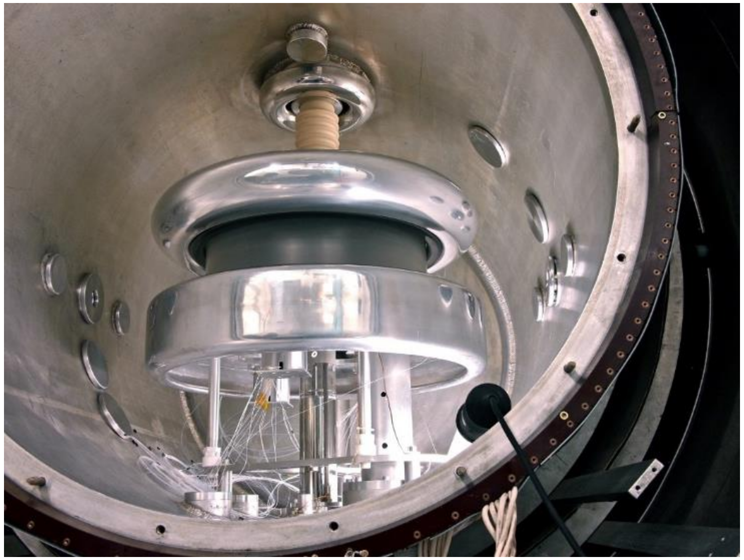
Allow large storage times



The nEDM experiment

nEDM collaboration : ~ 50 physicists from 8 countries and 16 labs

Data taken over two years (2015 and 2016) at PSI



Using the apparatus used at ILL by the RAL/sussex collaboration

54 068 cycles of 180 s in 99 magnetic configurations (sequence)

$\sim 11\,400$ UCN per cycle

Electric field: $\mathrm{E} \sim 11\ \mathrm{kV/cm}$

Magnetic field: $B_0 \sim 1\ \mu\mathrm{T}$

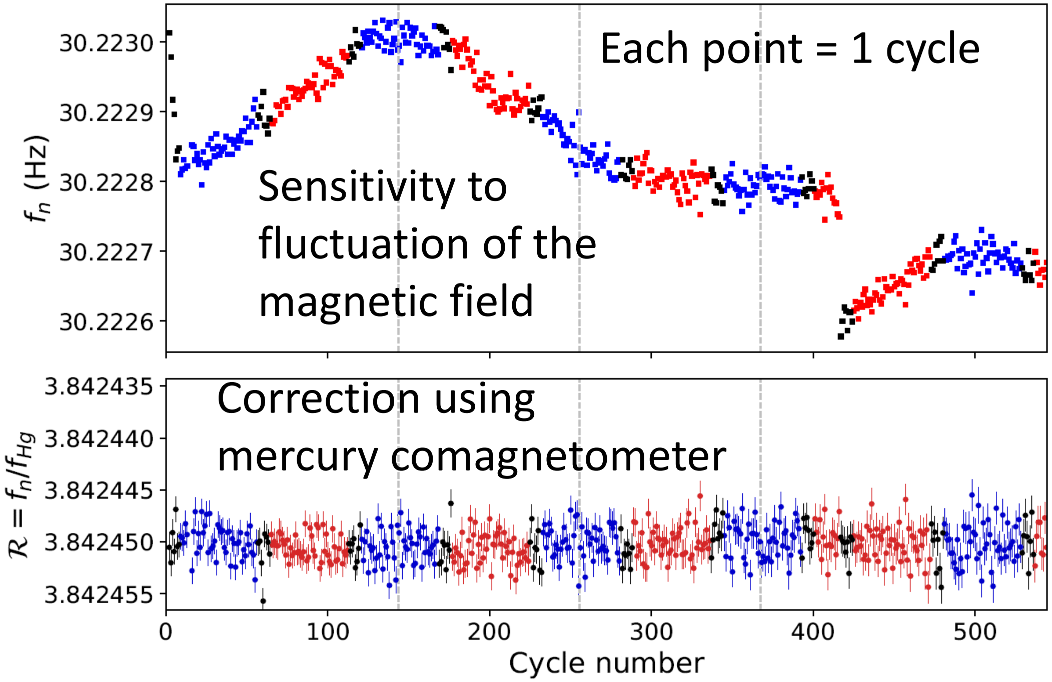
$$\boldsymbol{\sigma_{d_n} = \frac{\hbar}{2ET\alpha\sqrt{N_{\mathrm{tot}}}}}$$

Statistical sensitivity → $\mathbf{1,1 \times 10^{-26}}\boldsymbol{e}\ \mathbf{cm}$

Magnetic management

Controlling the magnetic field and gradients:

- By reducing the ambiant magnetic field :
  - Passive mu-metal shielding,
  - Active compensation coils,
  - Magnetic free environment.
- By measuring the field :
  - Cs magnetometers outside the chamber : field gradients,
  - Hg comagnetometer : measure (**almost**) the same field as seen by neutrons.



Each point = 1 cycle

Sensitivity to fluctuation of the magnetic field

Correction using mercury comagnetometer

But any effect on Hg measurement linearly dependent on $\vec{E}$ will induce a false Edm

Using magnetic gradients in the analysis

Fake Hg Edm combines :

- Relativistic vxE
- Magnetic inhomogeneities (« gradients »)

$$d_{n\leftarrow\mathrm{Hg}}^{\mathrm{false}} = \frac{\hbar\,\gamma_n\,\gamma_{\mathrm{Hg}}\,R^2}{8\,c^2}\left(\boldsymbol{G}_{\mathbf{grav}} + \widehat{\boldsymbol{G}}\right)$$

$\boldsymbol{G}_{\mathbf{Grav}}$: Due to gravity, there is an average height difference of gaseous Hg and ultracold neutrons $\langle z\rangle = -0{,}39\mathrm{cm}$ and feel slightly different fields. Both frequency ratio and false edm depends o nthis gradient

$\widehat{\boldsymbol{G}}$: higher order gradients

Analysis strategy

- Create magnetic gradients building various magnetic configurations
- For each configuration: fit $\mathcal{R}(E) = \dfrac{f_n}{f_{Hg}} = \boldsymbol{\mathcal{R}_0} - \dfrac{2\boldsymbol{d_n}}{\hbar|\gamma_n|B_0}E$

$$\mathcal{R}_0 = \left|\frac{\gamma_n}{\gamma_{\mathrm{Hg}}}\right|\left(1 + \frac{\langle z\rangle}{B_0}\boldsymbol{G}_{\mathbf{grav}} + \frac{\langle \boldsymbol{B_T^2}\rangle}{2B_0^2}\right) \qquad d_n = d_n^{true} + \frac{\hbar\,\gamma_n\,\gamma_{\mathrm{Hg}}\,R^2}{8\,c^2}\left(\boldsymbol{G}_{\mathbf{grav}} + \widehat{\boldsymbol{G}}\right)$$

- Use maps of the magnetic field to measure the gradients $\widehat{\boldsymbol{G}}$ and the transverse field inhomogeneities $\langle \boldsymbol{B_T^2}\rangle$

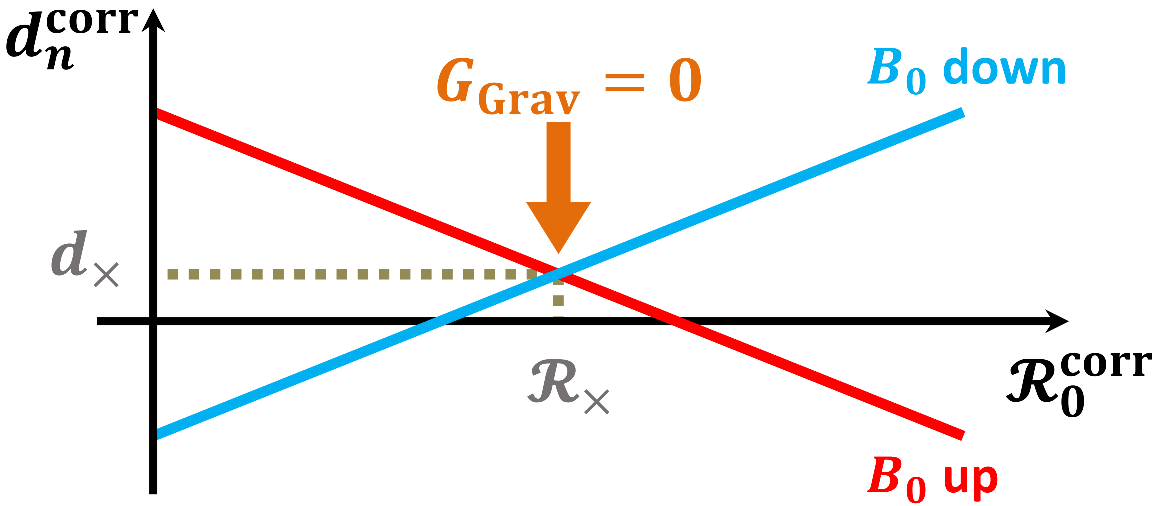
The crossing point

- After correction, we got 2 quantities that depend linearly on $\boldsymbol{G}_{\mathbf{grav}}$ with a known slope, $\pm\eta$ (sign depends on magnetic field sign)

$$d_n^{\mathrm{corr}} = d_n - \frac{\hbar\,\gamma_n\,\gamma_{\mathrm{Hg}}\,R^2}{8\,c^2}\hat{G} \qquad \mathcal{R}_0^{\mathrm{corr}} = \mathcal{R}_0 - \left|\frac{\gamma_n}{\gamma_{\mathrm{Hg}}}\right|\frac{\langle \boldsymbol{B}_{\boldsymbol{T}}^{\mathbf{2}}\rangle}{2B_0^2}$$

- The crossing of the two lines correspond to $\boldsymbol{G}_{\mathbf{grav}} = \mathbf{0}$ cancelling the false Edm term

$$d_\times = d_n - \frac{\hbar\,\gamma_n\,\gamma_{\mathrm{Hg}}\,R^2}{8\,c^2}\hat{G} = \boxed{d_n^{true}} + \cancel{\frac{\hbar\,\gamma_n\,\gamma_{\mathrm{Hg}}\,R^2}{8\,c^2}\boldsymbol{G}_{\mathbf{grav}}}$$



Systematics overview

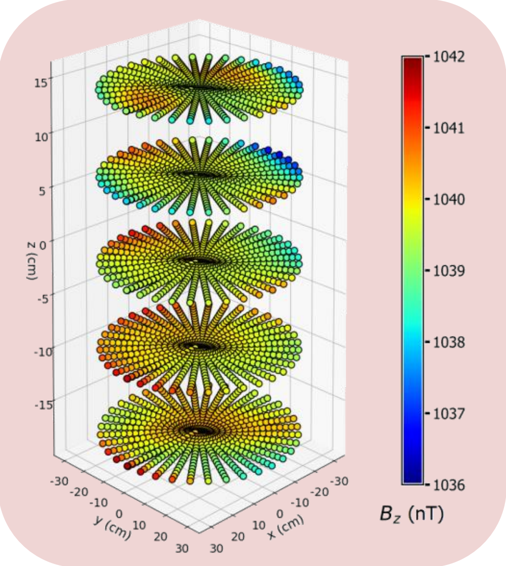
	Effect	shift	error
False Hg EDM	Error on $\langle z \rangle$	-	7
	Higher order gradients $\hat{G}$	69	10
	Transverse field correction $\langle B_T^2 \rangle$	0	5
	Hg EDM[8]	-0.1	0.1
Other effects	Local dipole fields	-	4
	$v \times E$ UCN net motion	-	2
	Quadratic $v \times E$	-	0.1
	Uncompensated G drift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

$\times 10^{-28}$ e. cm

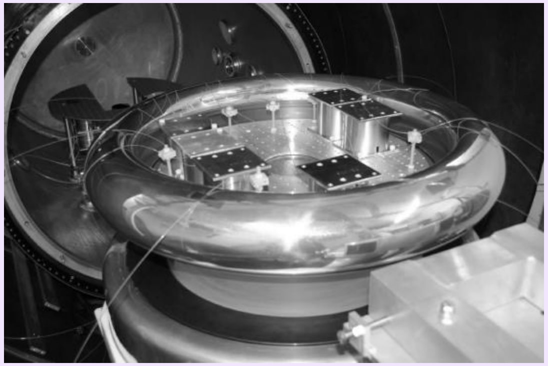
Final systematic :

$\pm 0.2 \times 10^{-26}$ e.cm

Field mapping



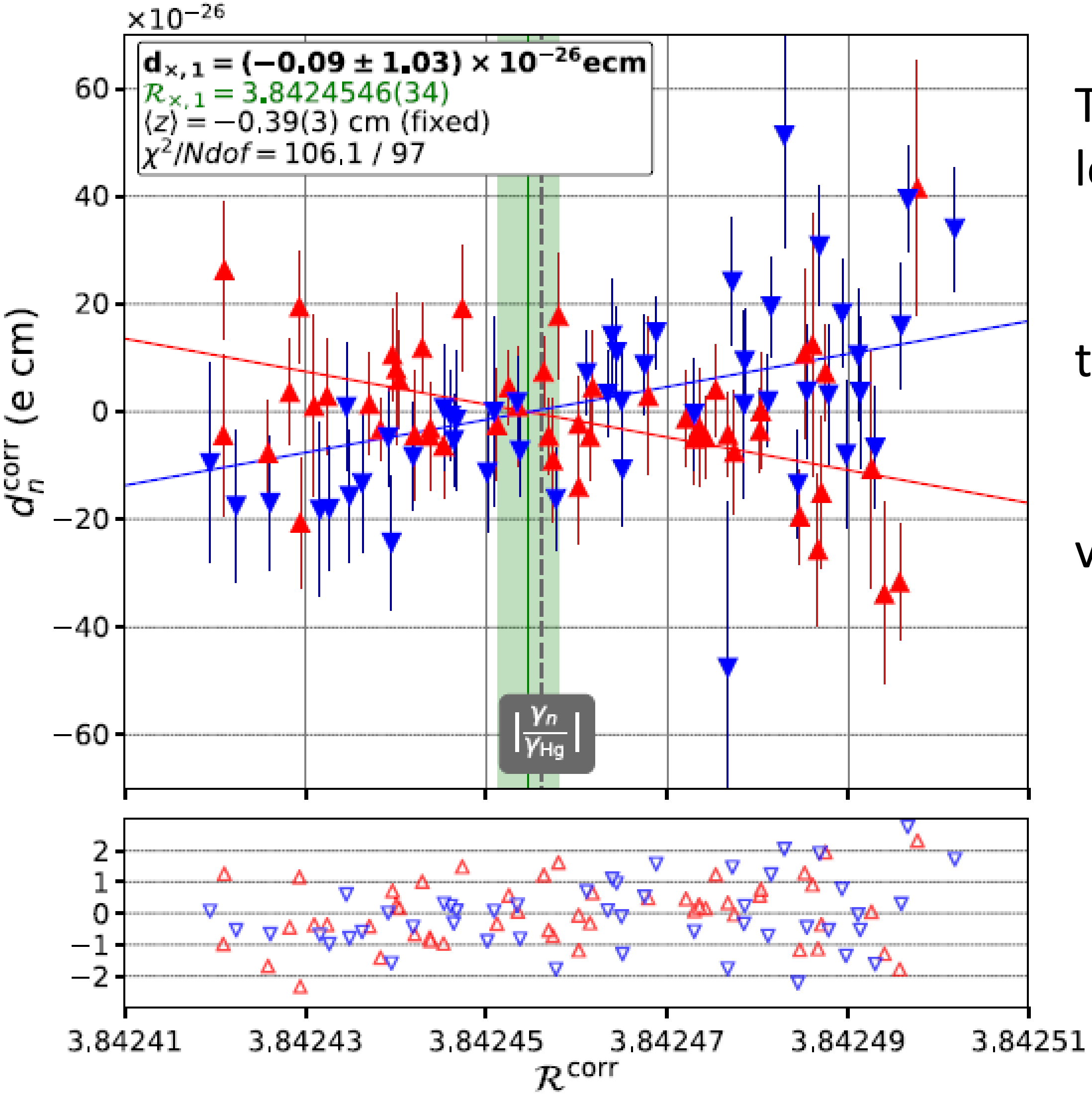
Cesium magnetometers



Optically Pumped Cs Magnetometers Enabling a High-Sensitivity Search for the Neutron EDM,
submitted to PRA

Scans for magnetic contaminations at PTB Berlin

Final result



Two analysis teams working on two level blinded data :

- optimize the selection and debug the analysis code independently

- **First unblinding** : check if central value are consistent between teams

- **Second unblinding** : Final results !

I → $(-0{,}09 \pm 1{,}03) \times 10^{-26}\ e$ cm

II → $(+0{,}15 \pm 1{,}07) \times 10^{-26}\ e$ cm

C. Abel *et al.* Phys. Rev. Lett. **124**, 081803 – Published 28 February 2020

$$d_n = (0,0 \pm 1,1_{stat} \pm 0,2_{syst}) \times 10^{-26}\ e\ \mathrm{cm}$$

Previous : $d_n = \left(-0.2 \pm 1.5_{stat} \pm 1.0_{syst}\right) \times 10^{-26}\ e\mathrm{cm}$

Coming next : n2EDM project

The nEDM collaboration has demonstrated its capacity to control systematic effects at a few $10^{-27}e\mathrm{cm}$

New spectrometer : 2022-…

Control of the magnetic field homogeneity and measurement : improved systematics

- Dual chamber apparatus : simultaneous measurement of both field configuration
- Colossal magnetic shield (6 mu-metal layers, $5 \times 5 \times 5\ \mathrm{m}^3$), shielding factor 100000
- Advanced magnetometry (external and comagnetometry)

Increase the electric field

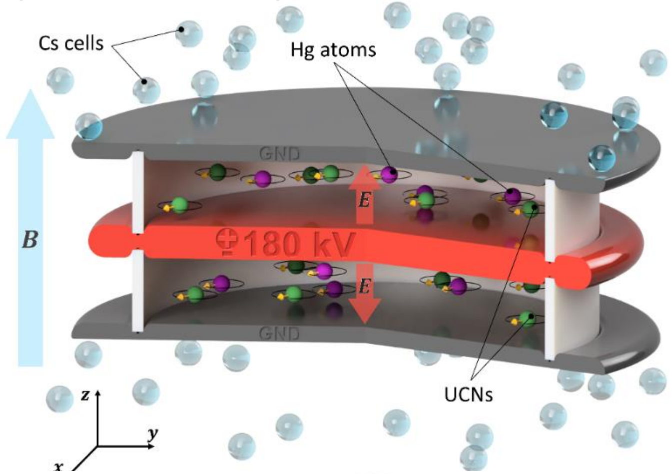
- 180 kV

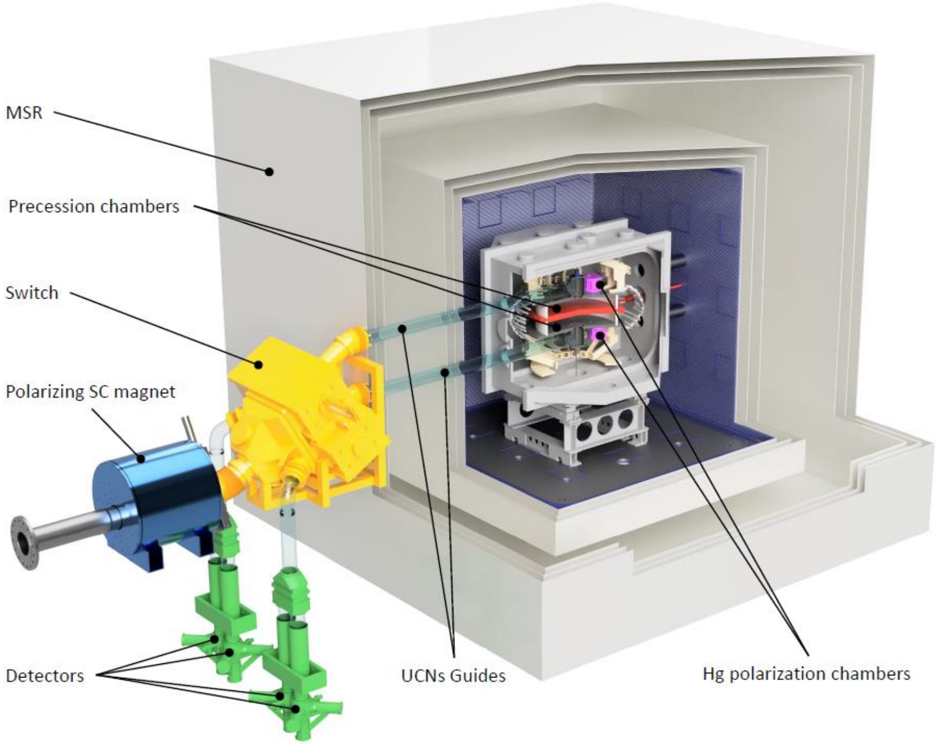
Increase the statistics

- 5 years data taking
- Larger chamber (Volume x 7)

Possible further improvement:
« magic field » to compensate
Systematic vxE effect in comagnetometer

G.Pignol 1812.01420





Conclusion

nEDM experiment result

New result on the neutron EDM by the nEDM collaboration (PSI):

$$\boldsymbol{d_n = (0,0 \pm 1,1_{\text{stat}} \pm 0,2_{\text{syst}}) \times 10^{-26}\ e\ \text{cm}}$$

Still (unfortunately) compatible with zero, translate into a limit:

$$\boldsymbol{d_n < 1.8 \times 10^{-26}\ e\ \text{cm}}\ \textbf{@ 90\% CL}$$

Improve the limit by a **factor 2.**

Systematics are reduced by a **factor 5**: Show a good understanding and control of the systematics effects.

n2EDM apparatus

- design includes our understanding of systematics to further improve the sensitivity.
- reduced statistical sensitivity (higher volume, higher E field)

GOAL : reach 10^{-27} e.cm in 2027

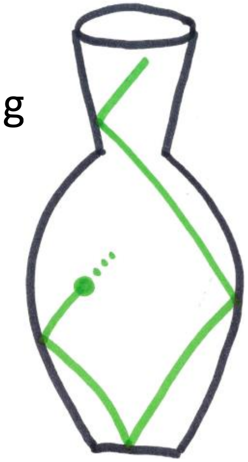
Extra material

Based on **ultra cold neutron storage** (all but one)

Neutron production : spallation or nuclear reactor + thermalisation + inelastic cooling (He-II or solid D_2)

Room temperature experiments : UCN need to be produced (source) then extracted/guided to the experimental chamber

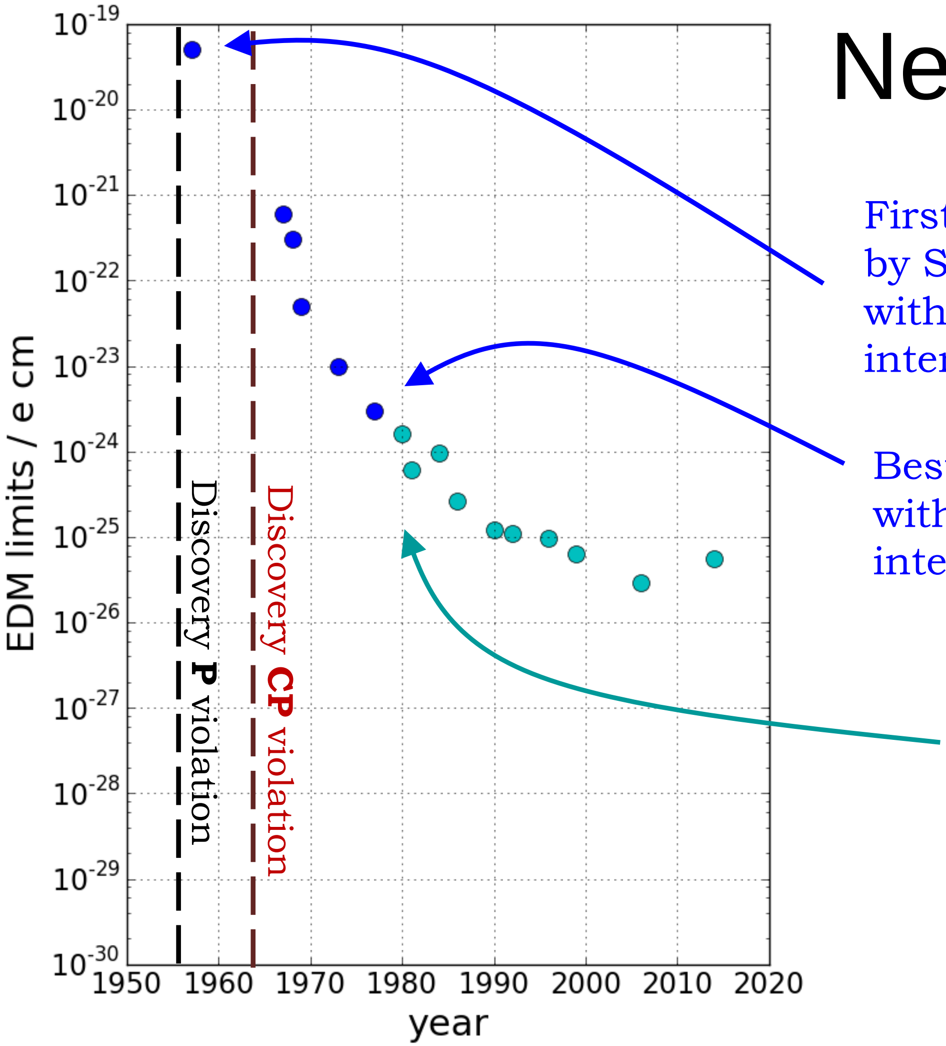
Cryogenic experiments : UCN production and EDM measurement takes place at the same place (in superfluid helium at 1K…)



Place	Neutron source	Concept	Stage/Readiness
SNS	Spallation + UCN production in situ	Cryogenic double chamber with helium comagnetometers	« large scale integration » phase
PSI	Spallation + sD2 UCN source	n2EDM: double Ramsey chamber with mercury comagnetometers	Source running, experiment under construction
LANL	Spallation + sD2 UCN source	double Ramsey chamber with mercury comagnetometers	Source running, experiment in design phase
TRIUMF	Spallation + superfluid He UCN source	double Ramsey chamber	Source under construction, experiment in conceptual phase
ILL	Reactor + superfluid He UCN source	panEDM: double Ramsey chamber, no comagnetometers	Source and experiment under construction
PNPI	WWR-M reactor + inpile superfluid He UCN source	Getting a really high density of UCNs	Source under construction
ESS	Spallation + Cold neutron beam	100m double beam + time of flight	Demonstration phase, small prototype operational @ ILL

Room temperature UCN experiments aiming at a precision of $\approx 1 \times 10^{-27} e\ \mathrm{cm}$

Neutron EDM history

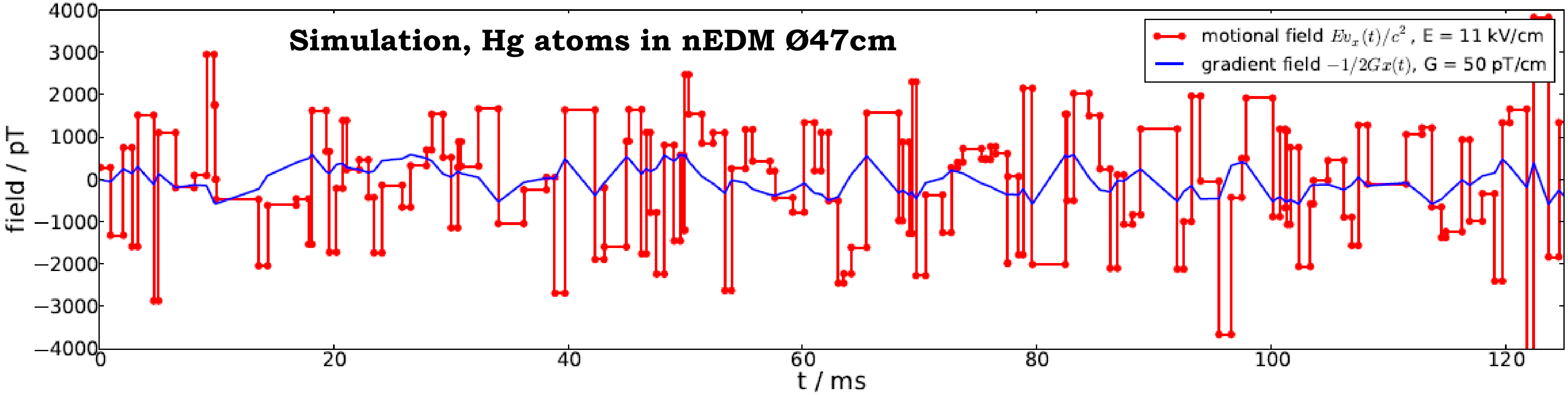


First experiment
by Smith, Purcell and Ramsey
with a **beam of thermal neutrons**,
interrogation time $T \approx 1$ ms

Best « beam » experiment in Grenoble
with **slower neutrons**,
interrogation time $T \approx 20$ ms

« Modern » experiments with
ultracold neutrons started.
interrogation time $T \approx 100$ s

The co-magnetometer problem: vxE/c^2



Frequency shift from a transverse magnetic noise $\underline{B}$

$$\delta f = \frac{\gamma^2}{4\pi}\int_0^\infty d\tau \, \mathrm{Im}\, e^{-i\omega\tau} \langle \underline{B}(0)\underline{B}^*(\tau)\rangle$$

Linear-in-E frequency shift (low B limit)

$$d^{\text{false}}_{n\leftarrow\text{Hg}} = -\frac{\hbar|\gamma_n\gamma_{\text{Hg}}|}{2c^2}\langle xB_x + yB_y\rangle$$

B-field uniformity is critical $G = 1\,\text{pT/cm} \leftrightarrow d^{\text{false}}_{n\leftarrow\text{Hg}} = 4.4\times 10^{-27} e\text{cm}$

From nEDM to n2EDM @ PSI

$$d_n < 3 \times 10^{-26}\, e.cm$$

$$d_n = \left(-0.2 \pm 1.5_{stat} \pm 1.0_{syst}\right) \times 10^{-26}\, ecm$$

1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012

ILL data production

RAL/Sussex collaboration

Transfer at PSI (new UCN source)
Various upgrade
New collaboration : nEDM

New appartus : n2EDM

PSI data

n2EDM installation and comissionning

n2EDM data…

2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027

$$d_n = \left(0.0 \pm 1.1_{stat} \pm 0.2_{syst}\right) \times 10^{-26}\, ecm$$

$$d_n < 1.8 \times 10^{-26}\, e.cm$$

Abel et al., PRL 124 081803 (2020)

Beyond SM contribution

SM contribution through EW loops : $d_n \approx 10^{-33} e\ \mathrm{cm}$

The QCD contribution : $\mathcal{L} = \frac{\alpha}{8\pi}\theta\, G^{\mu\nu}\widetilde{G_{\mu\nu}}$

No known mechanism to reduce θ to (nearly?) zero -> axions ?

$d_n \approx \theta \times 10^{-16}\ e\ \mathrm{cm}$
$\rightarrow \theta < 10^{-10}$
« Strong CP problem »

One loop contribution : for example MSSM contains ~40 CP violating imaginary parameters…

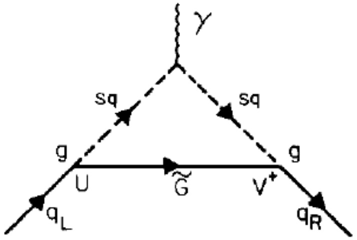


Fig. 2. One-loop diagram which may contribute to d_n in a softly broken susy model.

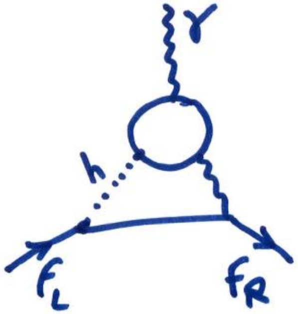
*Ellis, Ferrara, Nanopoulos, PLB **114** (1982).*
EDM induced by soft mass terms for squarks and gluinos

$$d_n \approx e\frac{\alpha}{4\pi}\frac{m_q}{M_{CPV}^2} \approx \left(\frac{1\ \mathrm{TeV}}{M_{CPV}}\right)^2 \times 10^{-25}\ e\ \mathrm{cm}$$

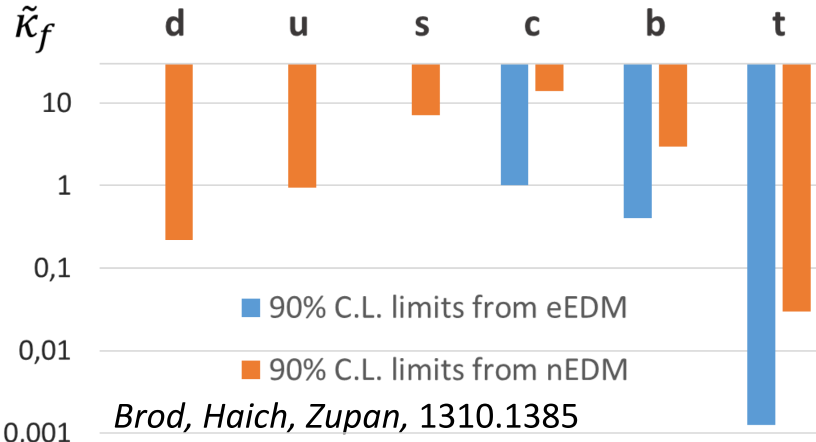
Two loops contribution :

Modified Higgs Yukawa coupling:

$$\mathcal{L} = -\frac{y_f}{\sqrt{2}}\left(\kappa_f \bar{f} f h + i\tilde{\kappa}_f\, \bar{f}\gamma_5 f h\right)$$



*Barr, Zee, PRL **65** (1990)*

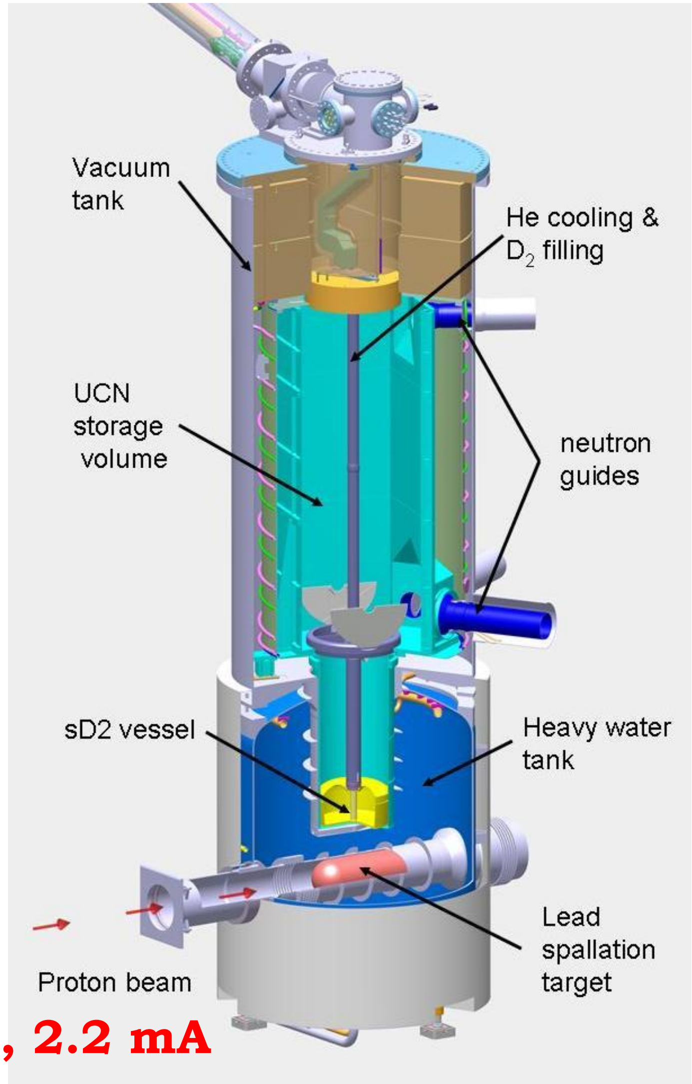


Brod, Haich, Zupan, 1310.1385
Brod, Stamou, 1810.12303
Brod, Skodras, 1811.05480

Ultracold neutrons @ PSI

UCN source at the
Paul Scherrer Institute

pulsed UCN source
One kick per 5 min
online since 2011



600 MeV, 2.2 mA