# Searching for neutron Electric Dipole Moment and dark matter candidates at the Paul Scherrer Institute

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## Neutron Electric Dipole Moment

***CP* violation:** The non-zero value of neutron Electric Dipole Moment (EDM) will be evidence for the existence of CP violating processes.

$$\begin{aligned} H &= -\mu\cdot\hat{\sigma}\cdot\vec{B} - d\cdot\hat{\sigma}\cdot\vec{E} &&= -\mu\cdot\hat{\sigma}\cdot\vec{B} - d\cdot\hat{\sigma}\cdot\vec{E} \\ \mathcal{P}H &= -\mu\cdot\hat{\sigma}\cdot\vec{B} - d\cdot\hat{\sigma}\cdot(-\vec{E}) &&= -\mu\cdot\hat{\sigma}\cdot\vec{B} + d\cdot\hat{\sigma}\cdot\vec{E} \\ \mathcal{T}H &= -\mu\cdot(-\hat{\sigma})\cdot(-\vec{B}) - d\cdot(-\hat{\sigma})\cdot\vec{E} &&= -\mu\cdot\hat{\sigma}\cdot\vec{B} + d\cdot\hat{\sigma}\cdot\vec{E} \end{aligned}$$

EDMs of elementary particles are the most sensitive probes in searching for CP symmetry violating processes, the presence of which is essential to explain, for example, the matter-antimatter asymmetry in the Universe.

**Measurement method:** Larmor precession of neutron spins in parallel and antiparallel magnetic and electric fields.

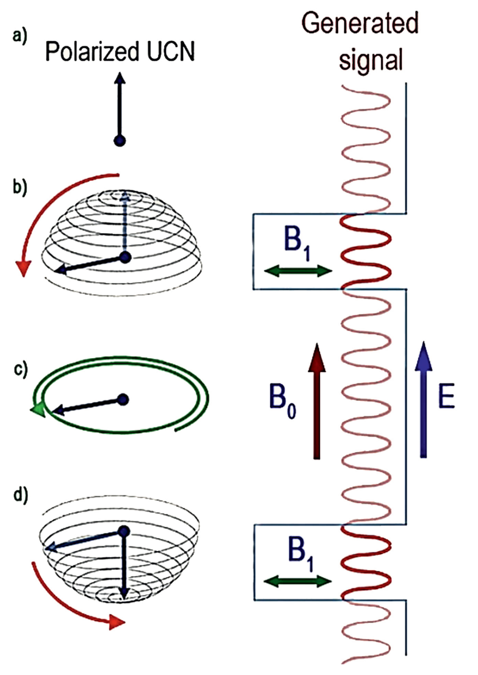
$$f_n^+ = \frac{2}{h}(\mu_n B_{\uparrow\uparrow} + d_n E_{\uparrow\uparrow}) \text{ for } \vec{B} \uparrow\uparrow \vec{E}, \quad f_n^- = \frac{2}{h}(\mu_n B_{\uparrow\downarrow} - d_n E_{\uparrow\downarrow}) \text{ for } \vec{B} \uparrow\downarrow \vec{E}.$$

$$\Delta f_n = f_n^+ - f_n^- = \frac{2}{h}[d_n(E_{\uparrow\uparrow} + E_{\uparrow\downarrow}) + \mu_n(B_{\uparrow\uparrow} - B_{\uparrow\downarrow})].$$

Hence neutron EDM: $\boldsymbol{d_n = \frac{1}{4E}[h\Delta f_n - \mu_n(B_{\uparrow\uparrow} - B_{\uparrow\downarrow})]}$.

Control of the magnetic field is crucial for this measurement, as its uncontrolled value can mimic the non-zero value of the neutron EDM.

### Ramsey method of separated oscillating fields.

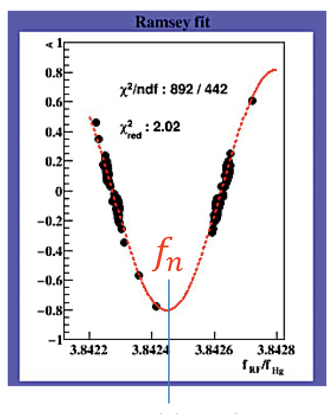



Sample of **polarized neutrons in magnetic** (1 μT) and electric (12 kV/cm) fields.

First 2s-long π/2 spin-flip pulse. Frequency equal to Larmor frequency (≈ 30Hz).

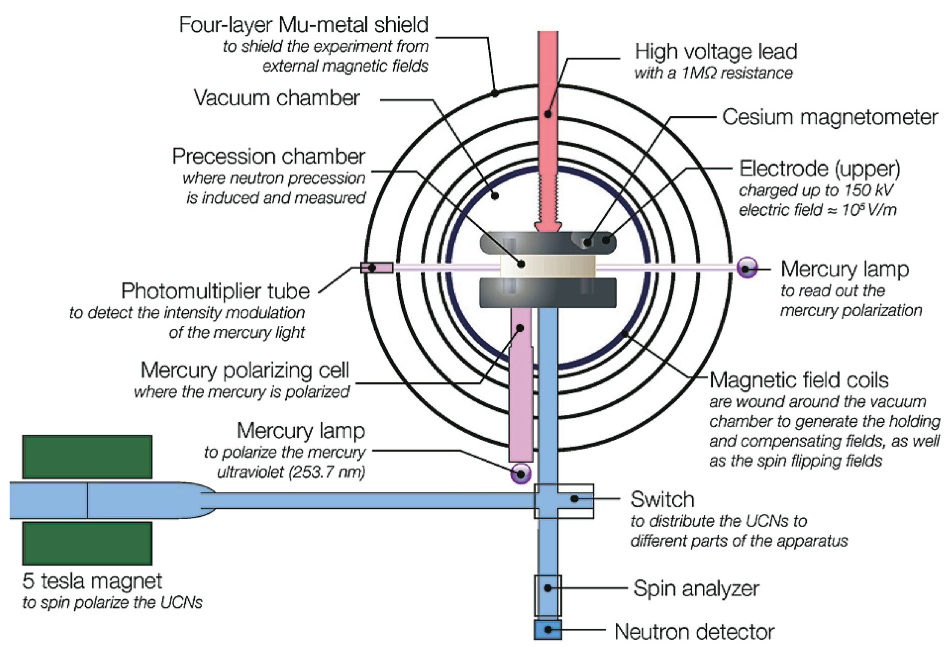
Free precession of neutron spin (180 s). Magnetic and electric fields parallel or antiparallel.

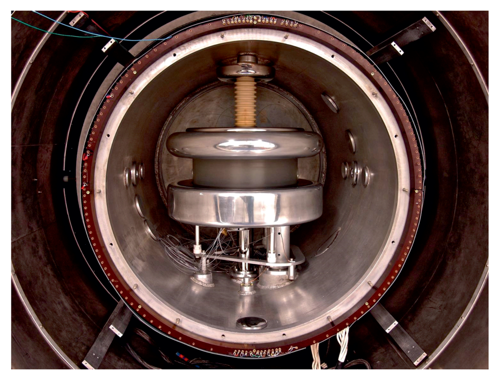
Second 2s-long π/2 spin-flip pulse. Rotation is not equal to π/2 if EDM ≠0.




Analysis of neutron polarization → asymmetry *A* of counted neutrons with spin ↑ and ↓ as a function of spin flip frequency divided by the Hg magnetometer frequency → $f_n$ resonant frequency.

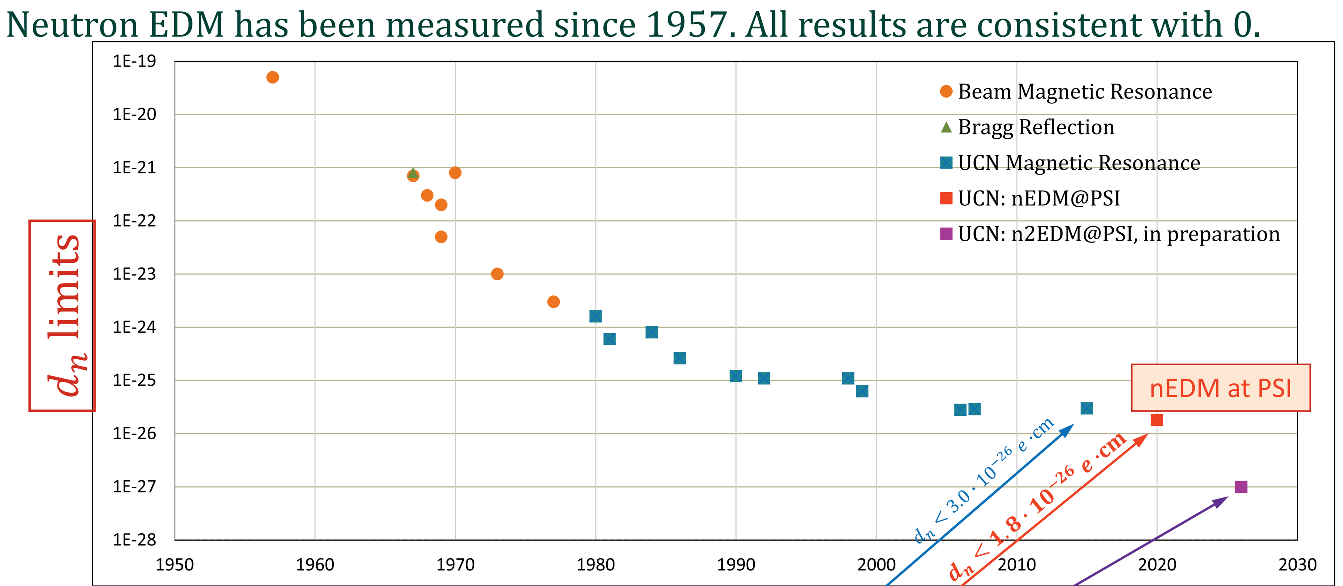
### Apparatus



### Results:

Neutron EDM has been measured since 1957. All results are consistent with 0.



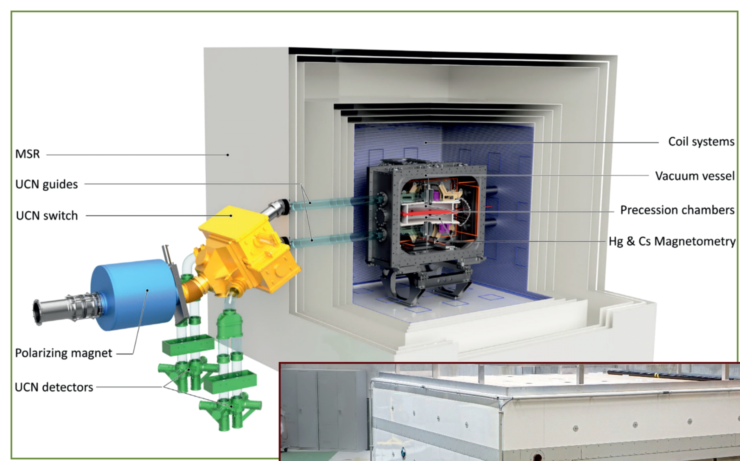

| | |
|---|---|
| RAL-Sussex-ILL | $d_n = (-0.2 \pm 1.5_{stat} \pm 1.0_{sys}) \cdot 10^{-26}\ e\cdot\text{cm}$ |
| nEDM at PSI | $d_n = (\ 0.0 \pm 1.1_{stat} \pm 0.2_{sys}) \cdot 10^{-26}\ e\cdot\text{cm}$ |
| n2EDM at PSI, in preparation, | assumed $d_n \lesssim 1 \cdot 10^{-27}\ e\cdot\text{cm}$ |

Fivefold reduction of systematic uncertainties.

Further reduction of systematic uncertainties, significant reduction of statistical uncertainty.

### n2EDM - upgraded apparatus

| | nEDM | n2EDM |
|---|---|---|
| Passive magnetic shield | 4 layers ($10^3$-$10^4$ factor), $\phi$2 m | 6 layers ($10^5$ factor), $L$ = 5 m |
| Precession chamber diameter | 1 chamber: $\phi$47 cm, $H$ = 11 cm | 2 chambers: - 80 cm, $H$ = 12 cm |
| Active magnetic shield | 3 coils | 8 coils |
| Cesium magnetometers | 16 | 112 |
| Electric field strength | 11 kV/cm | 15 kV/cm |
| Number of counted neutrons | 15 000/cycle | 121 000/cycle |
| $\sigma(d_n)$ per day | $11 \times 10^{-26}$ e cm | $2.6 \times 10^{-26}$ e cm |
| $\sigma(d_n)$ total | $9.5 \times 10^{-27}$ e cm | $1.1 \times 10^{-27}$ e cm |




For details, see https://www.psi.ch/en/edm

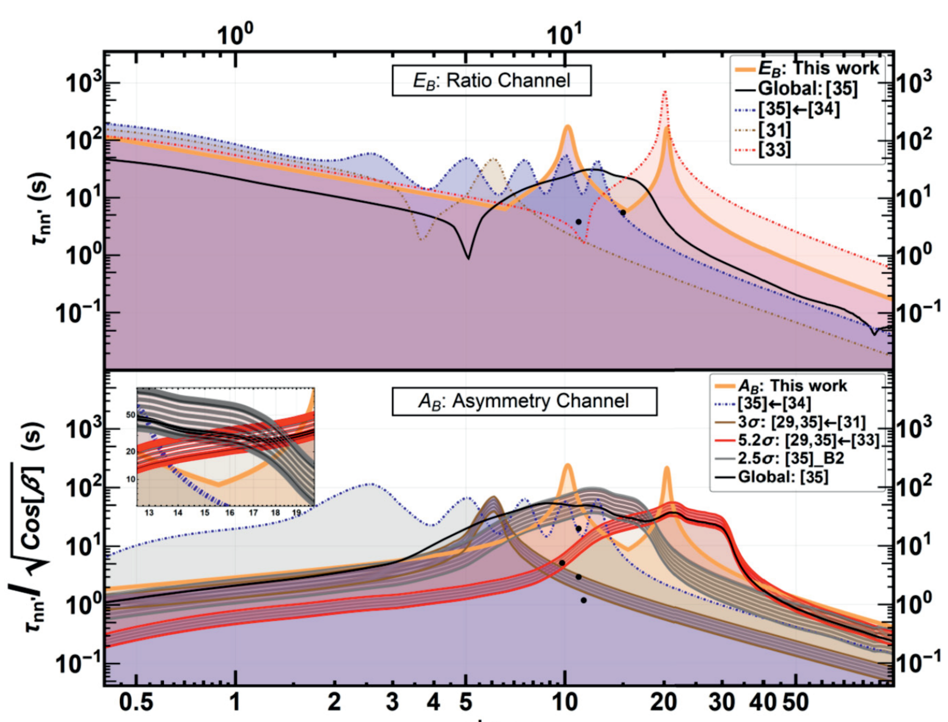
Results of the nEDM@PSI: Phys. Rev. Lett. 124 (2020) 081803.

Data blinding: EPJ A 57 (2021) 152.

New n2edm: EPJ C 81 (2021) 512, Rev. Sci. Instrum. 93 (2022) 095105.

## Neutron to mirror-neutron oscillations

Mirror world - proposed by T.D. Lee and C.-N, Yang (1956) to restore parity symmetry in the weak interaction. Ordinary particles would not interact with their mirror counterparts. Berezhiani and Bento pointed out (2006) that the characteristic time for neutron to mirror-neutron (n-n') oscillation can be of the order of a few seconds, i.e. small compared to the neutron lifetime. Mirror matter was considered as a dark matter candidate (1993).




Lower limits on the n-n' oscillation time $\tau_{nn'}$ while assuming mirror field B' ≠ 0.

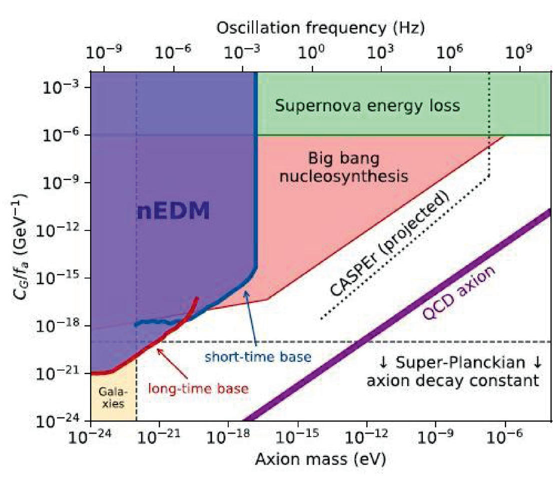
The following new lower limits on the oscillation time were obtained: $\tau_{nn'} > 352$ s at $B = 0$, $\tau_{nn'} > 6$ s for 0.4 μT < $B$ < 25.7 μT, and $\tau_{nn'}/\sqrt{\cos\beta} > 9$ s for 5.0 μT < $B$ < 25.4 μT, where β is the fixed angle between the applied magnetic field and the local mirror magnetic field, which is assumed to be bound to the Earth.

These new constraints are the best measured so far around $B$~10μT and 20μT.

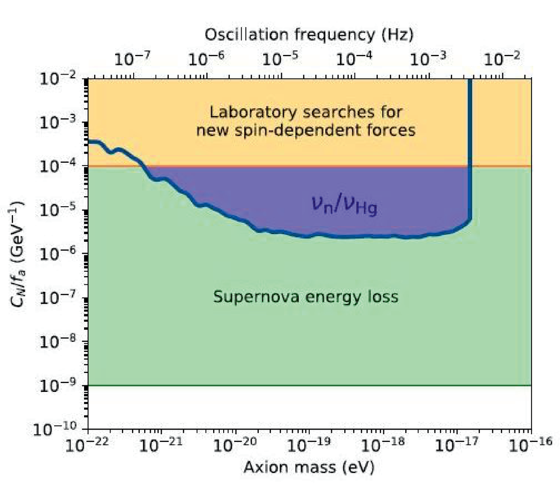
For details, see Physics Letters B 812 (2021) 135993.

## Search for axionlike dark matter

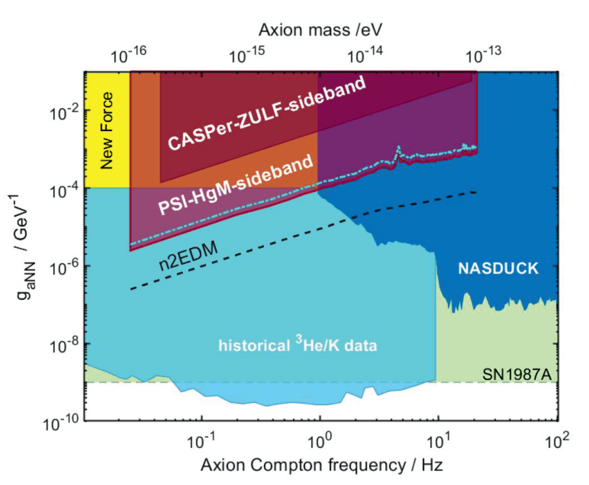
Analysis of ratio of frequencies of spin-precession of ultracold neutrons and $^{199}$Hg atoms enabled us to estimate an axion-induced oscillating electric dipole moment of the neutron and an axion-wind spin-precession effect. We performed a long- and short-time-base analysis using data from the RAL-Sussex-ILL and nEDM at PSI data, respectively. In addition, in our newest analysis we investigated axion-wind effect exploiting the spin precession of polarized $^{199}$Hg in a low magnetic field of $B$ = 1 μT. Our search covers the mass range of $10^{-24} \le m_a \le 10^{-17}$ eV ($f_n/f_{Hg}$) and $10^{-16} \le m_a \le 10^{-13}$ eV ($f_{Hg}$). Our null result sets the first laboratory constraints on the coupling of axion dark matter to gluons, which improve on astrophysical limits by up to 3 orders of magnitude, and also improves on previous laboratory constraints on the axion coupling to nucleons by up to a factor of 40.




$f_n/f_{Hg}$ analysis.
Limits on the interactions of an axion with the gluons, assuming that axions saturate the local cold DM content. The regions above the thick blue and red lines correspond to the regions of parameters excluded by us at the 95% confidence level.




$f_n/f_{Hg}$ analysis.
Similar to the left figure, but for the interactions of an axion with the nucleons.




$f_{Hg}$ analysis.
Exclusion plot for the axion-nucleon coupling parameter versus Compton frequency of the classical axion field, assuming that the axion field couples to neutrons and protons with the same strength. The red area is given by our present $^{199}$Hg-sideband analysis at PSI with a 95% confidence level.

For details, see

$f_n/f_{Hg}$: Physical Review X 7, 041034 (2017),

$f_{Hg}$: SciPost Phys. 15, 058 (2023).