Nuclear T,P-violating moments induce atomic and molecular EDM

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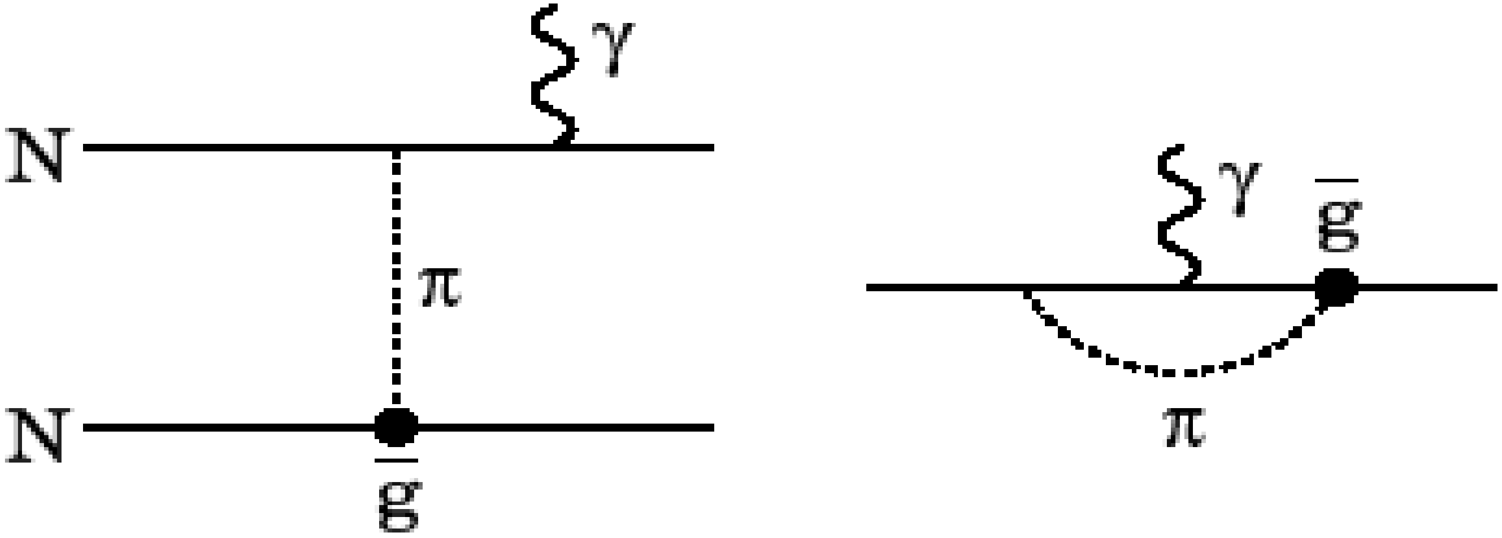
Nuclear Electric Dipole Moment: T,P-odd NN interaction gives 40 times larger contribution than nucleon EDM. Sushkov, Flambaum, Khriplovich 1984, x 10^1 - 10^3 in deformed nuclei



Nuclear EDM-screening: d_N E_N

- Schiff theorem: $E_N=0$, neutral systems
- Extension for ions and molecules:

Ion acceleration $a= Z_i\ eE/M$

Nucleus acceleration $a=Z\ eE_N/M$

$$E_N=E\ Z_i/Z$$

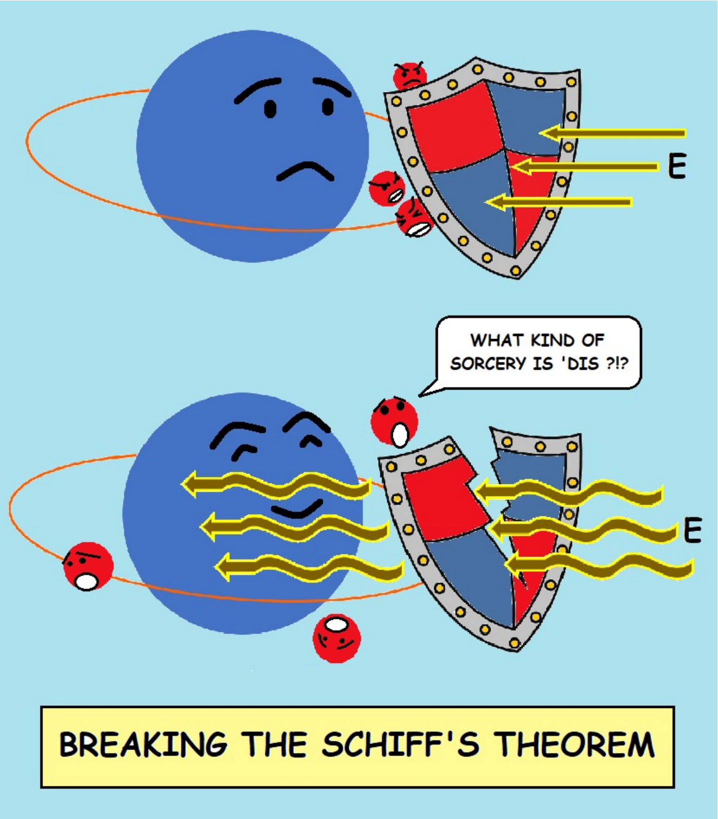
In molecules screening is stronger:

$a= Z_i\ eE/(M+m)$, $E_N= E\ (Z_i/Z)(M/(M+m))$

$Z_i =0 \rightarrow E_N= 0$

Breaking Schiff' s theorem

- Schiff' s theorem: **Constant** electric fields is screened.
- Our solution: **Oscillating** electric fields is **NOT** screened!



Nuclear EDM-screening: d_N E_N

- Oscillating field: incomplete screening!

V.F. 2018 $E_N=-E\,\varpi^2\,\alpha_{zz}/Z$

In resonance $E=A\sin\varsigma t\;\cos\varpi t$

$\varsigma=2eE_0<0|D_z|n>$ is the Rabi oscillation frequency

$A=\varpi^2 D_z$ x 5.14 10^9 V/cm

Extended screening theorem - molecules in oscillating electric field

- In **diatomic molecule** (V. F. , I. Samsonov and H. B. Tran Tan – Phys. Rev. A 99, 013430):

✓ $\frac{E_1}{E} = \sigma^{rot}, \sigma^{rot} = -\frac{2\omega^2\mu}{3Z_1}\frac{\bar{\omega}\bar{S}\bar{d}}{\bar{\omega}^2-\omega^2}$ if ω is in the rotational regime, E_1 is the field on the nucleus 1, E is the external field. Light nucleus dominate.

✓ $\frac{E_1}{E} = \sigma^{rot} + \sigma^{vib}, \sigma^{vib} = -\frac{2\omega^2\mu}{3Z_1}\sum_{vib\ states}\frac{\omega_{0n}S_0^n d_0^n}{\omega_{0n}^2-\omega^2}$ if ω is in the vibrational regime,

✓ $\frac{E_1}{E} = \sigma^{rot} + \sigma^{vib} + \sigma^{el}, \sigma^{el} = -\frac{\omega^2 M_1}{3(M_1+M_2)Z_1}(\alpha_{\parallel}^{el} + 2\alpha_{\perp}^{el})$ if ω is in the electronic regime.

- $\frac{E_1}{E} = \sigma^{rot}$ has large coefficient $\frac{\mu}{m_e}\sim 10^4$ (μ is the reduced nuclear mass). Nuclei moves slowly and do not provide efficient screening of oscillating field E. Small rotational energy denominator gives additional enhancement factor $\frac{\mu}{m_e}\sim 10^4$. Resonance gives an additional enhancement.

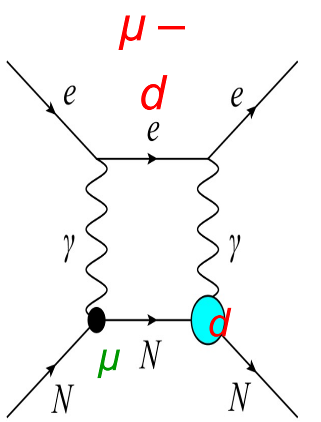
V.F., Tran Tan: Effects of oscillating nuclear EDMs induced by axion

- Axion dark matter field is oscillating → **nuclear EDMs is oscillating**.
- Oscillating nuclear EDMs → oscillating atomic/molecular EDMs.
- **Large enhancement for molecules**.
- **Huge enhancement in resonance** → good for detection.
- Oscillating nuclear EDMs → Atomic & Molecular transitions.

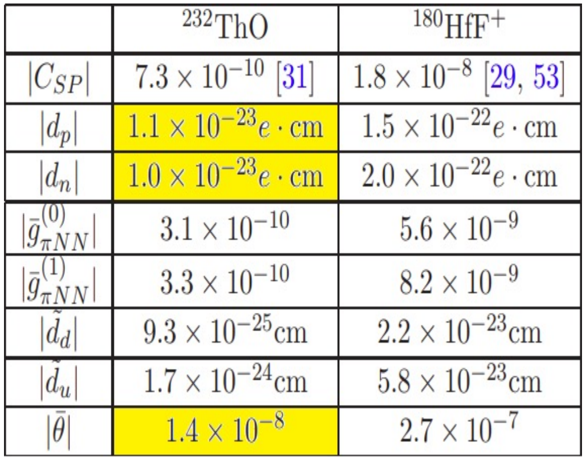
$$E_{\mathrm{Nucl}} = -\frac{m}{m_e}\frac{\omega^2\alpha}{Z}E_0 \qquad d_{\mathrm{atom}} = -\frac{m}{m_e}\frac{\omega^2\alpha}{Z}d_{\mathrm{Nucl}}$$

P,T-odd nuclear polarization

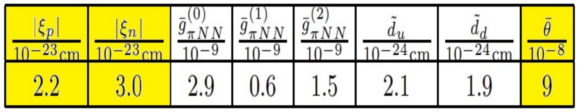
- atomic EDM due to nuclear T,P-odd polarizability.
- electric + magnetic vertices instead of 2 electric vertices for usual polarisabilty
- We studied this → electron EDM experiments are sensitive to hadron CP-violation, theta-term, axion dark matter, etc.



Internal nuclear excitations



	^{232}ThO	^{180}HfF$^+$
$\lvert C_{SP}\rvert$	7.3×10^{-10} [31]	1.8×10^{-8} [29, 53]
$\lvert d_p\rvert$	$1.1 \times 10^{-23} e \cdot \mathrm{cm}$	$1.5 \times 10^{-22} e \cdot \mathrm{cm}$
$\lvert d_n\rvert$	$1.0 \times 10^{-23} e \cdot \mathrm{cm}$	$2.0 \times 10^{-22} e \cdot \mathrm{cm}$
$\lvert\bar{g}^{(0)}_{\pi NN}\rvert$	3.1×10^{-10}	5.6×10^{-9}
$\lvert\bar{g}^{(1)}_{\pi NN}\rvert$	3.3×10^{-10}	8.2×10^{-9}
$\lvert\tilde{d}_d\rvert$	$9.3 \times 10^{-25}\mathrm{cm}$	$2.2 \times 10^{-23}\mathrm{cm}$
$\lvert\tilde{d}_u\rvert$	$1.7 \times 10^{-24}\mathrm{cm}$	$5.8 \times 10^{-23}\mathrm{cm}$
$\lvert\bar{\theta}\rvert$	1.4×10^{-8}	2.7×10^{-7}



$\frac{\lvert\xi_p\rvert}{10^{-23}\mathrm{cm}}$	$\frac{\lvert\xi_n\rvert}{10^{-23}\mathrm{cm}}$	$\frac{\bar{g}^{(0)}_{\pi NN}}{10^{-9}}$	$\frac{\bar{g}^{(1)}_{\pi NN}}{10^{-9}}$	$\frac{\bar{g}^{(2)}_{\pi NN}}{10^{-9}}$	$\frac{\tilde{d}_u}{10^{-24}\mathrm{cm}}$	$\frac{\tilde{d}_d}{10^{-24}\mathrm{cm}}$	$\frac{\bar{\theta}}{10^{-8}}$
2.2	3.0	2.9	0.6	1.5	2.1	1.9	9

Limits on $\xi_{p,n}$, $\bar{g}^{(0,1,2)}_{\pi NN}$, $\tilde{d}_{u,d}$ and $\bar{\theta}$ obtained from the ThO limit on $|C_{SP}| < 7.3 \times 10^{-10}$.

V.V. Flambaum, J.S.M. Ginges, G. Mititelu, arXiv:nucl-th/0010100 (2000)
V.V. Flambaum, M. Pospelov, A. Ritz, and Y.V. Stadnik, PRD 102, 035001 (2020)
V.V. Flambaum, I.B. Samsonov, H.B. Tran Tan, JHEP 2020, 77 (2020)
V.V. Flambaum, I.B. Samsonov, H.B. Tran Tan, PRD 102, 115036 (2020)

Diamagnetic atoms and molecules
Source-nuclear Schiff moment

SM appears when screening of external electric field by atomic electrons is taken into account.

Nuclear T,P-odd moments:

- EDM – non-observable due to total screening (Schiff theorem)

Nuclear electrostatic potential with screening (our 1984 calculation following ideas of Schiff and Sandars):

$$\varphi(\mathbf{R})=\int\frac{e\rho(\mathbf{r})}{|\mathbf{R}-\mathbf{r}|}d^3r+\frac{1}{Z}(\mathbf{d}\bullet\nabla)\int\frac{\rho(\mathbf{r})}{|\mathbf{R}-\mathbf{r}|}d^3r$$

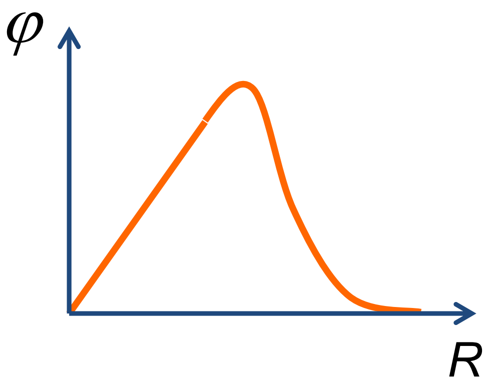
d is nuclear EDM, the term with **d** is the electron screening term

φ(**R**) in multipole expansion is reduced to $\varphi(\mathbf{R})=4\pi\mathbf{S}\bullet\nabla\delta(\mathbf{R})$

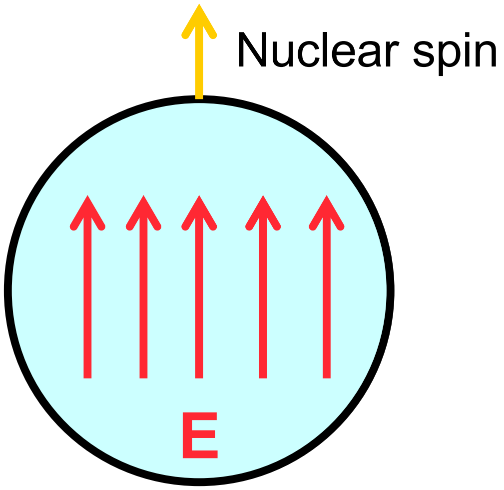
where $\mathbf{S}=\frac{e}{10}\left[\langle r^2\mathbf{r}\rangle-\frac{5}{3Z}\langle r^2\rangle\langle\mathbf{r}\rangle\right]$ is Schiff moment.

This expression is not suitable for relativistic calculations since electron wave function is infinite on the point-like nucleus.

Flambaum, Ginges, 2002: $\varphi(\mathbf{R}) = -\frac{3\mathbf{S}\bullet\mathbf{R}}{B}\rho(R)$ where $B = \int \rho(R) R^4 dR$



Electric field induced by T,P-odd nuclear forces which influence proton charge density



This potential has no singularities and may be used in relativistic calculations. Schiff moment electric field polarizes atom and produce EDM.

Relativistic corrections originating from electron wave functions can be incorporated into *Local Dipole Moment* (**L**)

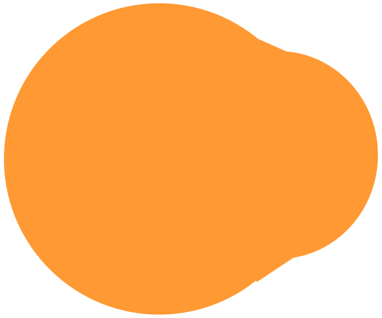
$$\mathbf{L} = \sum_{k=1}^{\infty} \mathbf{S}_k$$

$$\varphi(\mathbf{R}) = 4\pi\mathbf{L}\bullet\nabla\delta(\mathbf{R})$$

Nuclear enhancement

Auerbach, Flambaum, Spevak 1996

The strongest enhancement is due to octupole deformation (Rn,Ra,Fr,…)

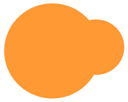


Intrinsic Schiff moment:

$$S_{\text{intr}} \approx eZR_N^3 \frac{9\beta_2\beta_3}{20\pi\sqrt{35}}$$

$\beta_2 \approx 0.2$ - quadrupole deformation

$\beta_3 \approx 0.1$ - octupole deformation



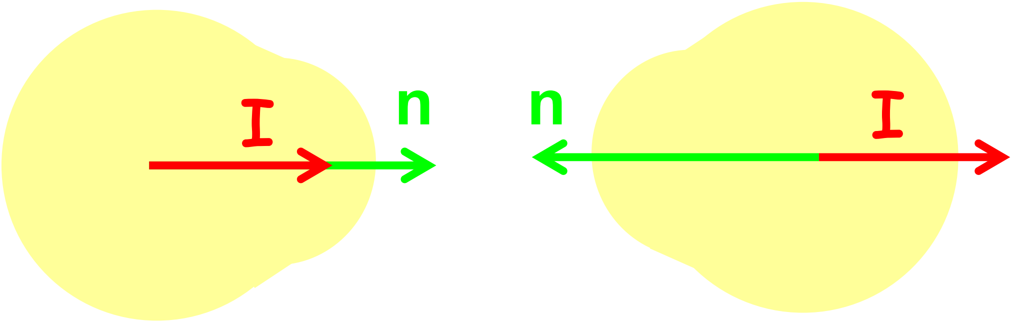
No T,P-odd forces are needed for the Schiff moment and EDM in intrinsic reference frame

However, in laboratory frame S=d=0 due to rotation

In the absence of T,P-odd forces: doublet (+) and (-)

$$\Psi = \frac{1}{\sqrt{2}}\left(\left| IMK \right\rangle + \left| IM-K \right\rangle \right)$$

and $\langle \mathbf{n} \rangle = 0$



T,P-odd mixing (β) with opposite parity state (-) of doublet:

$$\Psi = \frac{1}{\sqrt{2}}\left[(1+\beta)\left| IMK \right\rangle + (1-\beta)\left| IM-K \right\rangle \right]$$

and $\langle \mathbf{n} \rangle \propto \beta \mathbf{I}$

EDM and Schiff moment

$$\langle d \rangle, \langle \mathbf{S} \rangle \propto \langle \mathbf{n} \rangle \propto \beta \mathbf{I}$$

Simple estimate (Auerbach, Flambaum, Spevak):

$$S_{lab} \propto \frac{\langle + | H_{TP} | - \rangle}{E_+ - E_-} S_{body}$$

Three factors of enhancement:

1. Large collective moment in the body frame
2. Small energy interval (E_+-E_-), 0.05 instead of 8 MeV
3. Large matrix element <IMK | H_{TP}|IMK>

$$S \approx 0.05 e \beta_2 \beta_3^2 Z A^{2/3} \eta r_0^3 \frac{\mathrm{eV}}{E_+ - E_-} \approx 700 \times 10^{-8} \eta e \mathrm{fm}^3 \approx 500 S(\mathrm{Hg})$$

^{225}Ra,^{223}Rn, Fr,… -100-1000 times enhancemnt

Engel, Friar, Hayes (2000); Flambaum, Zelevinsky (2003): Static octupole deformation is not essential, nuclei with soft octupole vibrations also have the enhancement.

Many recent experiments and calculations confirm existence of octupole

EDMs of atoms of experimental interest

Z	Atom	[*S*/(e fm3)]*e* cm	$[10^{-25}\,\eta]$ *e* cm	Expt.
2	^{3}He	0.00008	0.0005	
54	^{129}Xe	0.38	0.7	Seattle, Ann Arbor, Heidelberg, …
70	^{171}Yb	-1.9	3	Bangalore,Kyoto
80	^{199}Hg	-2.8	4	Seattle
86	^{223}Rn	3.3	3300	TRIUMF
88	^{225}Ra	-8.2	2500	Argonne,KVI
88	^{223}Ra	-8.2	3400	

Standard Model $\eta = 0.3\ 10^{-8}$ $d_n = 5 \times 10^{-24}\ e\ \mathrm{cm}\ \eta$, $d(^{199}\mathrm{Hg})/\ d_n = 10^{-1}$

Octupole deformation and enhanced Schiff moments in long-lifetime nuclei

V.F. and Feldmeier 2019; V.F. and Dzuba 2019

^{225}Ra lifetime15 days –experiment in Argonne laboratory

^{227}Ac 22 years, atomic EDM 6 times larger than in Ra

^{237}Np 2 million years , EDM 4 times larger than in Ra

^{153}Eu stable, EDM comparable to Ra ?

Other candidates: ^{233,235}U (0.7 billion years),^{161,163}Dy (stable), ^{229}Th (8 thousand years),

^{229}Pa (unstable but possibly huge SM due to very close nuclear level– 60 eV ?,

Close levels enhancement of EDM in ^{229}Pa noted in Haxton, Henly 1983

Ra, Th, Eu, Ac, Np molecules

Enhancement factors

- Biggest Schiff moment
- Highest nuclear charge
- Close rotational levels of opposite parity

(strong internal electric field in polar molecules)

Largest T,P-odd nuclear spin-axis interaction $\kappa(I\ n)$

^{225}RaO= 200 TlF

V.F. 2008;

Kudashov,Petrov,Skripnikov,Mosyagin, Titov, V.F. 2013,

^{227}AcF, ^{227}AcN, ^{227}AcO$^+$, ^{229}ThO, ^{153}EuO$^+$ and ^{153}EuN.

V.F., Feldmeier 2019;

V.F. ,Dzuba 2019

Skripnikov, Mosyagin, Titov, V. F. 2020, ^{227}AcN=^{227}AcO$^+$ =400 TlF

Enhancement in nuclei with quadrupole deformation

Close level of opposite parity

- Haxton, Henley –EDM, MQM
- Sushkov, Flambaum, Khriplovich –Schiff and magnetic quadrupole moments

Magnetic interaction is not screened!

Khriplovich, Sushkov, Flambaum- MQM produces EDM in atoms and molecules

Atomic EDMs

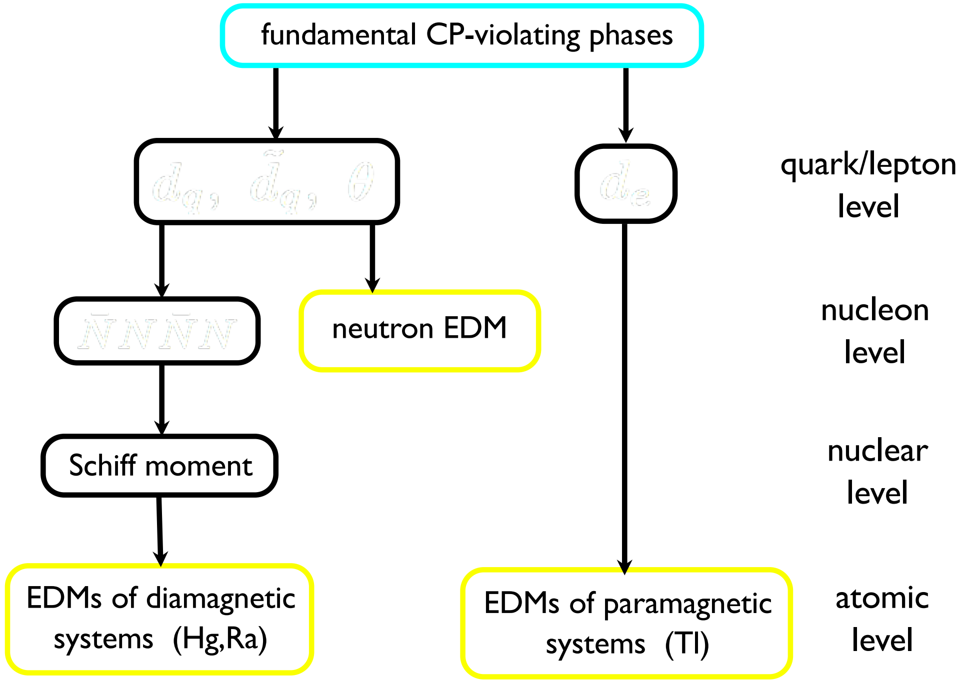
Atomic limits

$|d(^{199}\mathrm{Hg})| < 10^{-29}\ e\ \mathrm{cm}$
(95% c.l., Seattle, 2016)

$|d(^{205}\mathrm{Tl})| < 9.6 \times 10^{-25}\ e\ \mathrm{cm}$
(90% c.l., Berkeley, 2002)

$|d(\mathrm{n})| < 2.9 \times 10^{-26}\ e\ \mathrm{cm}$
(90% c.l., Grenoble, 2006)

Leading mechanisms for EDM generation



fundamental CP-violating phases

$d_q,\ \tilde{d}_q,\ \theta$

d_e

quark/lepton level

$\bar{N}N\bar{N}N$

neutron EDM

nucleon level

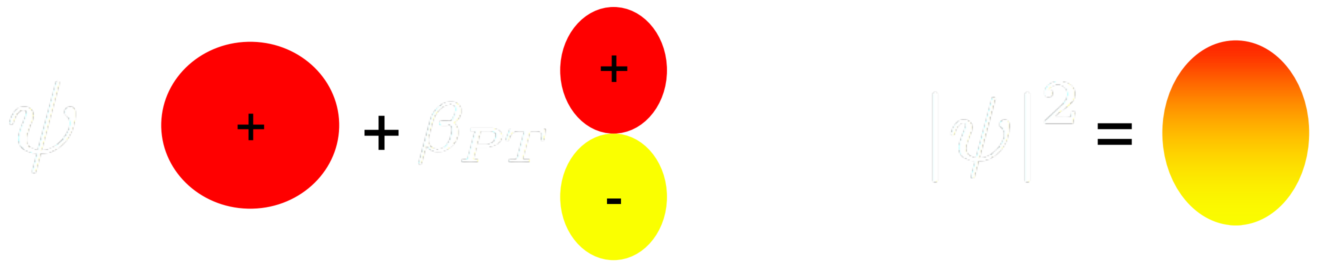
Schiff moment

nuclear level

EDMs of diamagnetic systems (Hg,Ra)

EDMs of paramagnetic systems (Tl)

atomic level



Atomic EDM produced by nuclear magnetic quadrupole moment

MQM produced by nuclear T,P-odd forces

V.F. 1994: Collective enhancement in deformed nuclei

Mechanism: T,P-odd nuclear interaction produces spin hedgehog- correlation (s r)

Spherical – magnetic monopole forbidden

Deformed- collective magnetic quadrupole

Nuclear and molecular calculations of MQM effects

- V.F. , DeMille, Kozlov PRL 2014

Nuclear and molecular estimates for

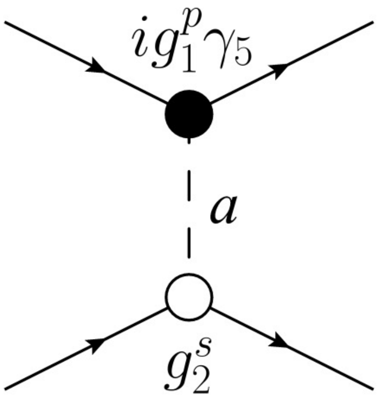
TaN, ThO, BaF, HgF, YbF, HfF+

(TaO+, WN+)

Accurate molecular calculations

- ThO: Skripnikov, Petrov, Titov and V.F. 2014
- TaN: Skripnikov, Petrov, Mosyagin, Titov, and V.F. 2015,
- HfF+ Petrov,Skripnikov, Titov, and V.F. 2017, 2018
- YbOH Maison, Skripnikov and V.F. 2019
- LuOH+ Maison, Skripnikov, V.F., Grau 2020

EDM produced by axion exchange



$$\mathcal{L}_{aff} = a \sum_f \bar{f} \left(g_f^s + i g_f^p \gamma_5 \right) f$$

$$V_{12}(r) \approx \frac{g_1^p g_2^s}{8\pi m_1} \boldsymbol{\sigma} \cdot \hat{\boldsymbol{r}} \left(\frac{m_a}{r} + \frac{1}{r^2} \right) e^{-m_a r}$$

- Macroscopic fifth-forces [Moody, Wilczek, *PRD* 30, 130 (1984)]

- *P*,*T*-violating forces => Atomic and Molecular EDMs
[Stadnik, Dzuba, Flambaum PRL 2018, Dzuba,Flambaum,Samsonov,Stadnik 2018]

Atomic EDM experiments: Cs, Tl, Xe, Hg

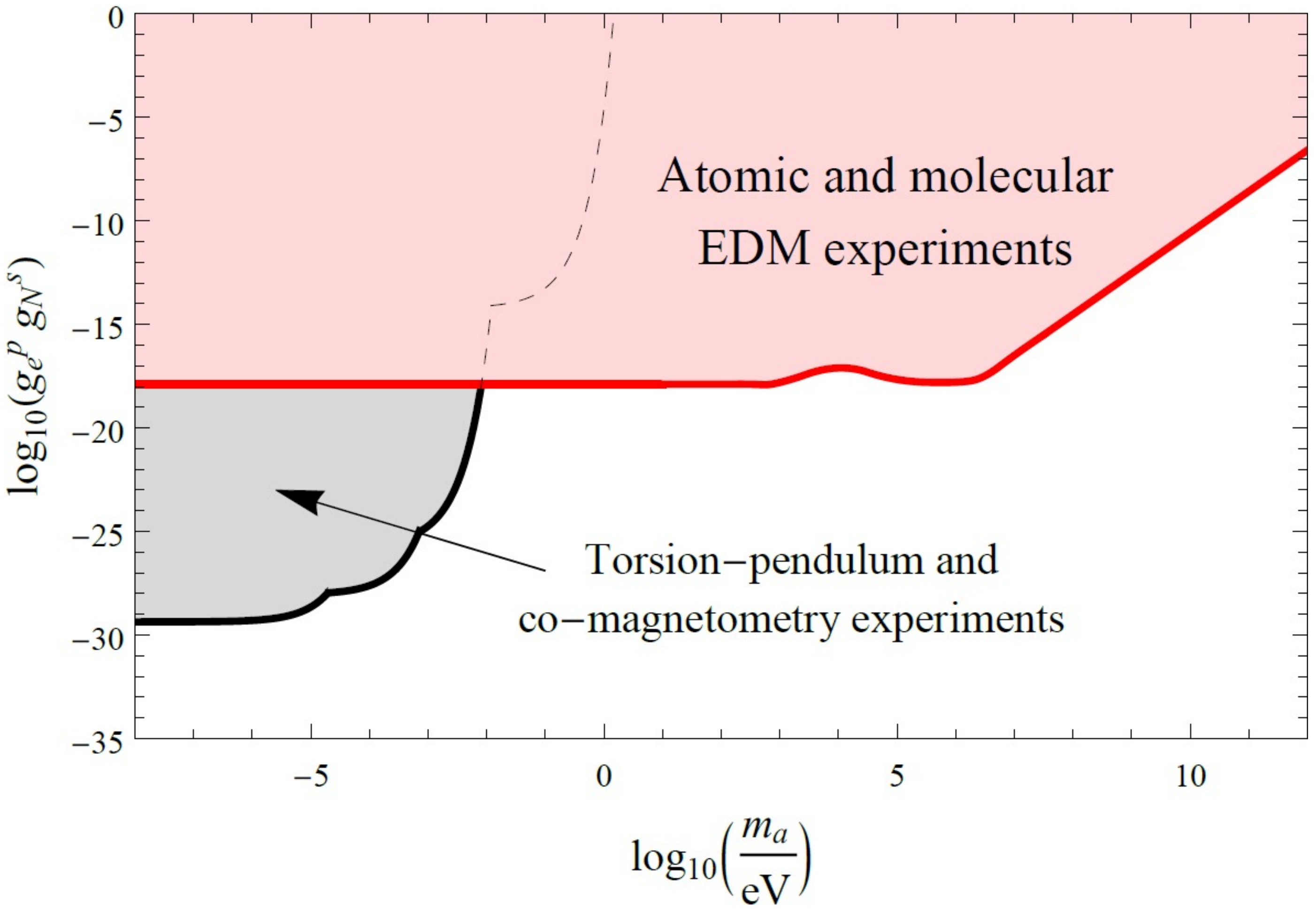
Molecular EDM experiments: YbF, HfF$^+$, ThO

YbOH Maison,Flambaum,Hutzler,Skripnikov 2021

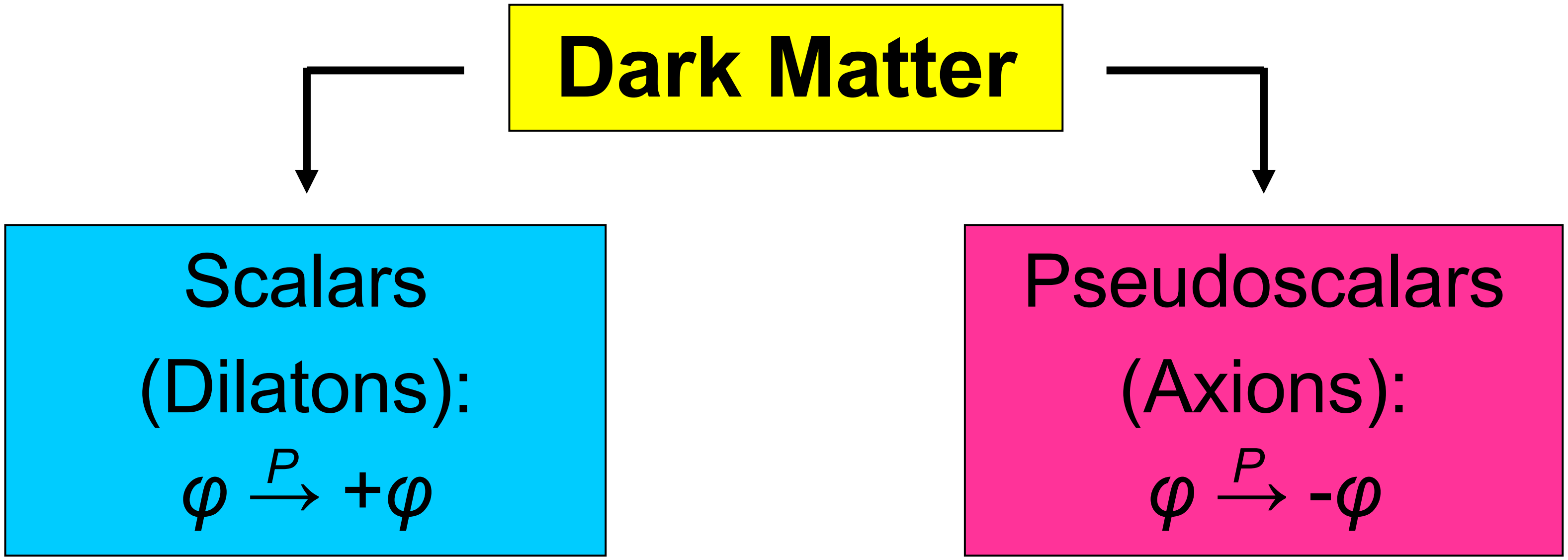
Constraints on Scalar-Pseudoscalar Nucleon-Electron Interaction

EDM constraints: [Stadnik, Dzuba , Flambaum PRL 2018]

Many orders of magnitude improvement!



Low-mass Spin-0 Dark Matter



Dark Matter

Scalars

(Dilatons):

$\varphi \xrightarrow{P} +\varphi$

Pseudoscalars

(Axions):

$\varphi \xrightarrow{P} -\varphi$

→ Time-varying fundamental constants

10^{15} improvement

→ Time-varying spin-dependent effects, EDM

10^{3} improvement

Low-mass Spin-0 Dark Matter

- *Low-mass spin-0 particles* form a *coherently oscillating classical* field $\varphi(t) = \varphi_0 \cos(m_\varphi c^2 t/\hbar)$, with energy density $\langle\rho_\varphi\rangle \approx m_\varphi^2 \varphi_0^2/2$ ($\rho_{\mathrm{DM,local}} \approx 0.4$ GeV/cm^3)
- Coherently oscillating field, since *cold* ($E_\varphi \approx m_\varphi c^2$)
- Classical field for $m_\varphi \leq 0.1$ eV, since $n_\varphi(\lambda_{\mathrm{dB},\varphi}/2\pi)^3 \gg 1$
- Coherent + classical DM field = "Cosmic maser"
- 10^{-22} eV $\leq m_\varphi \leq 0.1$ eV <=> 10^{-8} Hz $\leq f \leq 10^{13}$ Hz

$\lambda_{\mathrm{dB},\varphi} \leq L_{\text{dwarf galaxy}} \sim 1$ kpc

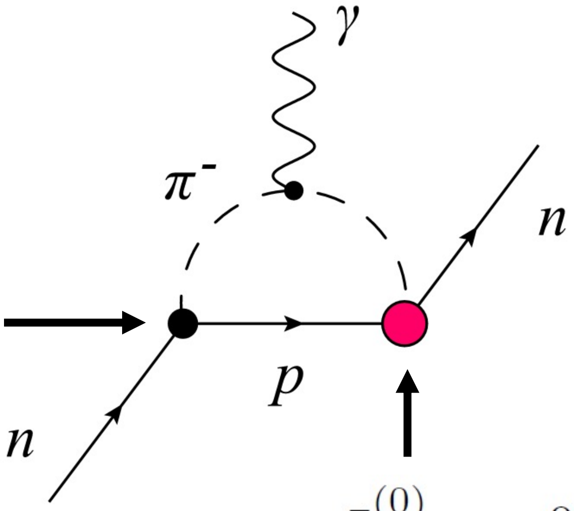
Classical field

- $m_\varphi \sim 10^{-22}$ eV <=> $T \sim 1$ year

Axion-Induced Oscillating Neutron EDM

[Crewther, Di Vecchia, Veneziano, Witten, *PLB* 88, 123 (1979)],
[Pospelov, Ritz, *PRL* 83, 2526 (1999)], [Graham, Rajendran, *PRD* 84, 055013 (2011)]

$$\mathcal{L}_{aGG} = \frac{C_G a_0 \cos(m_a t)}{f_a} \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \quad => \quad d_n(t) \propto \cos(m_a t)$$



$g_{\pi NN} = 13.5$

$\bar{g}^{(0)}_{\pi NN} \approx 0.016\ C_G a_0 \cos(m_a t)/f_a$

Axion-Induced Oscillating Atomic and Molecular EDMs

[O. Sushkov, Flambaum, Khriplovich, *JETP* 60, 873 (1984)],
[Stadnik , Flambaum, *PRD* 89, 043522 (2014)]

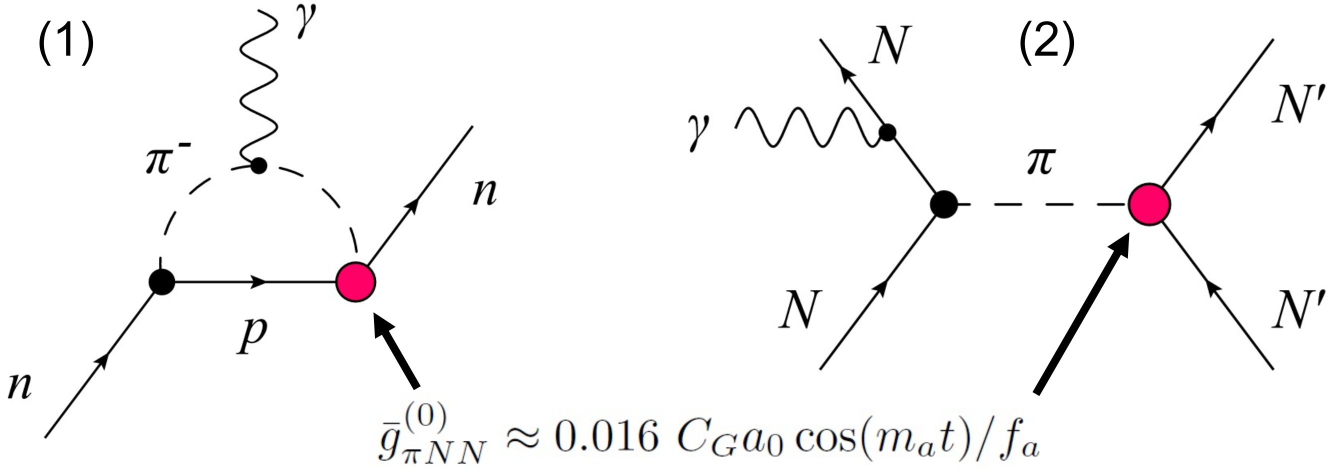
Induced through *hadronic mechanisms*:

- Oscillating nuclear Schiff moments ($I \geq 1/2 \Rightarrow J \geq 0$)
- Oscillating nuclear magnetic quadrupole moments ($I \geq 1 \Rightarrow J \geq 1/2$; *magnetic* => no Schiff screening)

Underlying mechanisms:

(1) Intrinsic oscillating nucleon EDMs (1-loop level)

(2) Oscillating *P*,*T*-violating intranuclear forces (*tree level* => **larger by ~4π² ≈ 40**; up to **extra 1000-fold enhancement** in deformed nuclei)

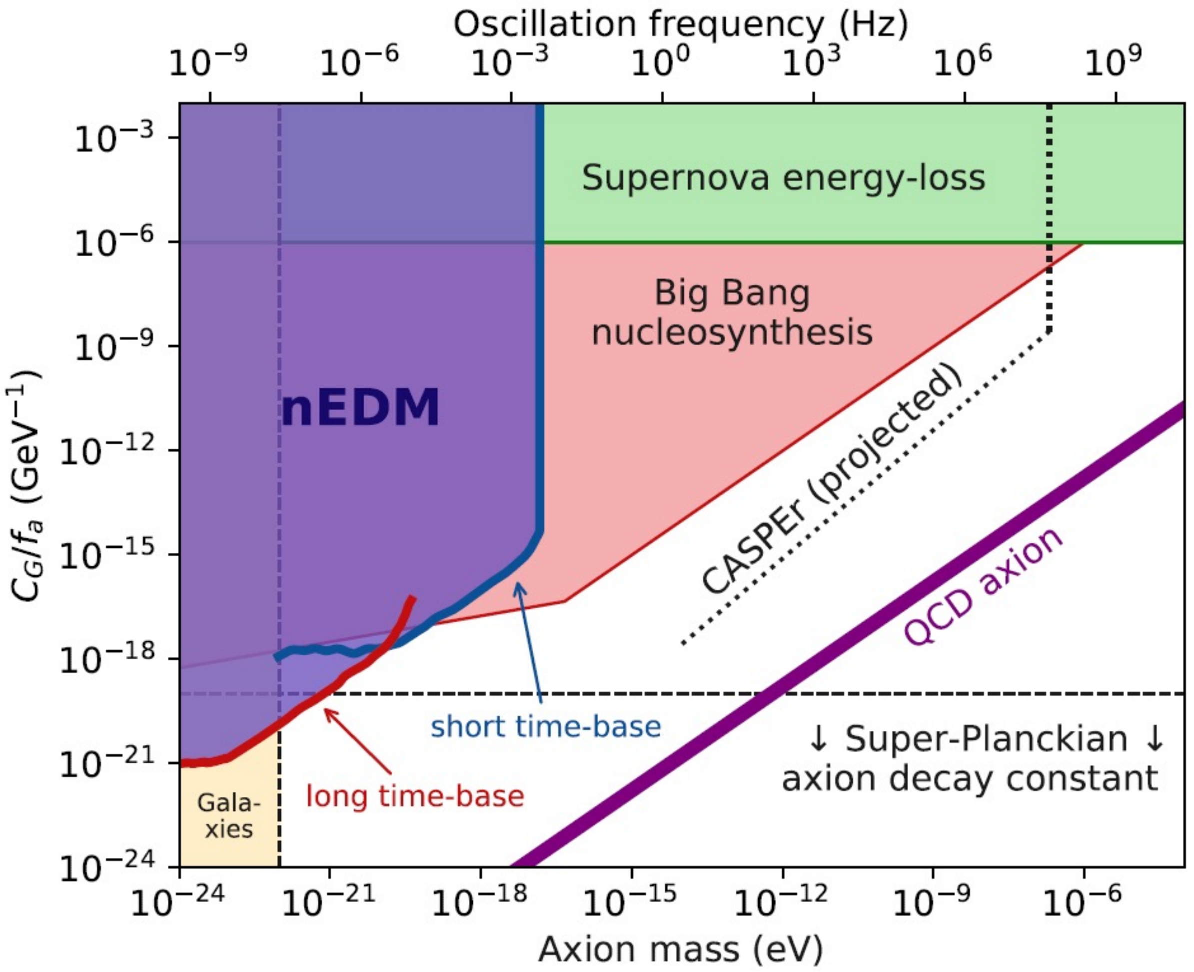


$$\bar{g}^{(0)}_{\pi NN} \approx 0.016\ C_G a_0 \cos(m_a t)/f_a$$

Constraints on Interaction of Axion Dark Matter with Gluons

nEDM constraints: [nEDM collaboration, PRX 2017]

3 orders of magnitude improvement!



OSCILLATING NUCLEAR ELECTRIC DIPOLE, MAGNETIC QUADRUPOLE AND SCHIFF MOMENTS, INDUCED BY AXIONIC DARK MATTER, PRODUCE MOLECULEAR TRANSITIONS

M2 transtion: photon suppressed, axion is not suppressed!

Smaller systematics

V.F., Tran Tan, Budker, Wickenbrock Phys. Rev. D 101, 073004 (2020)

Flambaum , Budker, Wickenbrock, arxiv: 1909.04970
Flambaum, Tran Tan, Budker, Wickenbrock, arxiv: 1910.07705

Summary

Schiff moment is enhanced up to 1000 times in nuclei with octupole deformation
→ radioactive molecules RaO, AcN, ThO, Np ,…

Stable EuN ? Nuclear spin *I* ≥ ½

Magnetic quadrupole moment has collective nature in nuclei with quadrupole deformation. YbF, HfF+, YbOH,TaN, ThO, …

Nuclear spin *I* ≥ 1, electron *J* ≥ 1/2; *magnetic* interaction => no Schiff screening

T,P-violating nuclear polarization gives atomic and molecular EDM , may be measured in molecules used to search for electron EDM : ThO, HfF+, …

Any nuclear spin including I=0, electron *J* ≥ 1/2

Schiff theorem is violated by oscillating electric field, resonance enhancement in molecules

Axion exchange produces static EDM, limits from molecular EDM experiments ThO, HfF+, also from Hg and Xe EDM experiments

Axion dark matter field produces oscillating EDM

nEDM collaboration, CASPEr electric, JILA (E. Cornell and Jun Ye group)

Axion dark matter field produces M2 transitions in molecules induced by oscillating nuclear magnetic quadrupole,

E1 by oscillating EDM and Schiff moments