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

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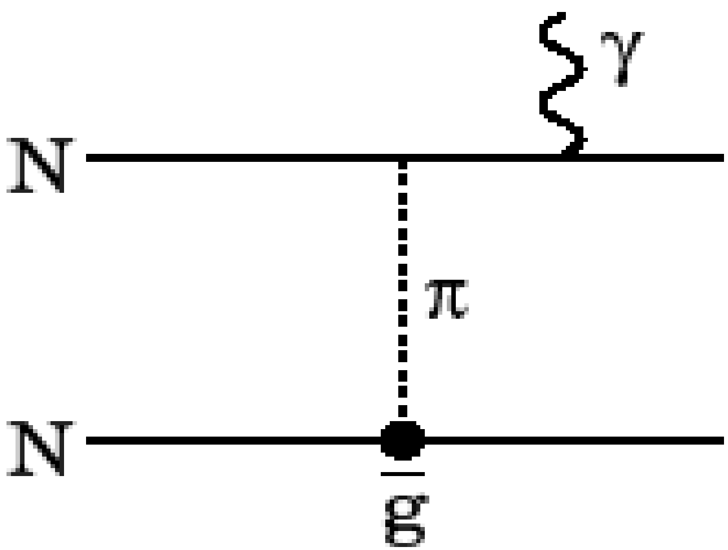
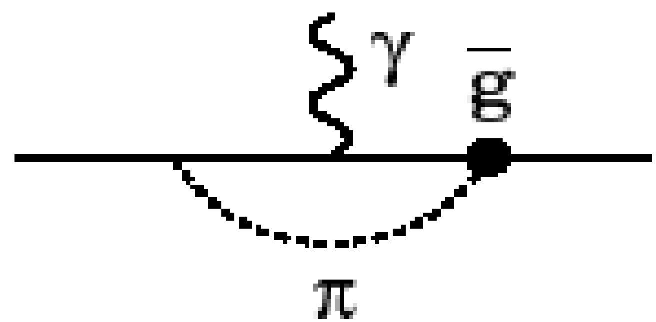
Nuclear Electric Dipole Moment: T,P-odd NN interaction gives 40 times larger contribution than nucleon EDM. Sushkov, Flambaum, Khriplovich 1984, x 10^1 - 10^3 in deformed nuclei





Nuclear EDM is screened in atoms: 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:

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

$Z_i =0 \rightarrow E_N= 0$

Violation of Schiff theorem in non-stationary states. V.F. 2023

Non-stationary states may be expanded as a sum of stationary states
$c_1|1> + c_2|2> + \dots$
Electric field on the nucleus

$$< E_z^t >= -\frac{2(\epsilon_1 - \epsilon_2)^2 m}{Ze^2\hbar^2} c_1 c_2 < 1|D_z|2 > \cos\left(\frac{(\epsilon_1 - \epsilon_2)t}{\hbar}\right).$$

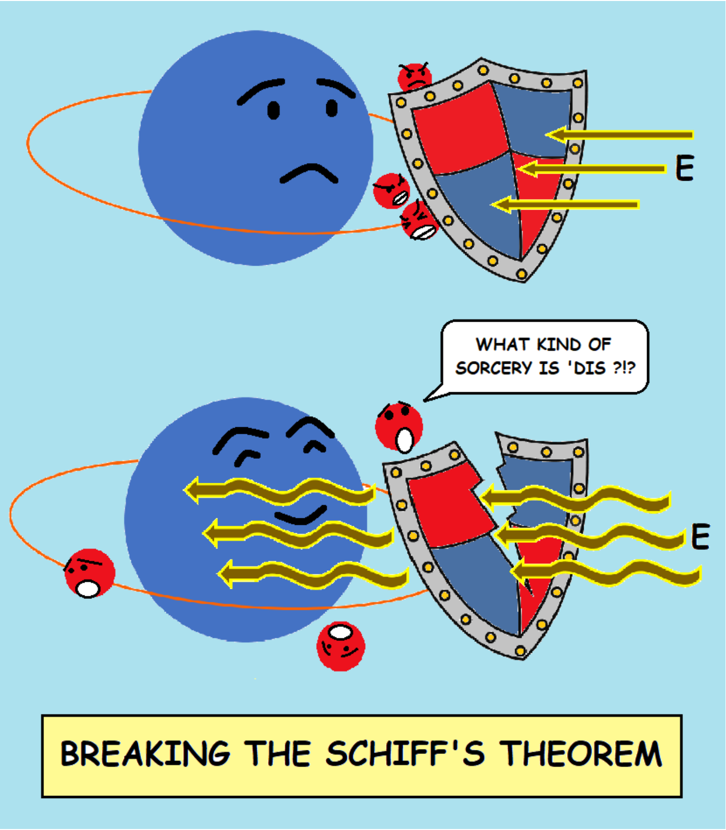
In atoms $m=m_e$ is electron mass.

In molecules $m=M_N$ is nuclear mass, since nuclei also produce screening in stationary case. Nuclei are very slow in molecules. They are not efficient screeners in time-dependent case. Field in molecules is M_N/m_e ~ 3-5 orders of magnitude bigger than in atoms.

Atomic unit of electric field is 5×10^9 V/cm, so, in principle, electric field on the nucleus may be several orders of magnitude bigger than fields used to measure neutron and atomic EDM. However, the field is strongly suppressed if energy difference=frequency of oscillations is small compare to atomic unit 27 eV.

Breaking Schiff’ s theorem

- Schiff’ s theorem: **Constant** electric fields is screened.
- Solution: **Oscillating** electric fields is **NOT** screened!



Nuclear EDM-screening: d_N E_N

- Oscillating field: incomplete screening!

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

  In molecules field is much bigger, by factor $(M_{mol}/m_e)^2$, since nuclei moves slowly and do not provide efficient screening

V.F. , Samsonov, Tran Tan 2019

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

$\varsigma = 2eE_0 \langle 0|D_z|n\rangle$ is the Rabi oscillation frequency

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

Violation of the Schiff theorem due to magnetic interaction

- Magnetic interaction + electric interaction=zero force acting on the atomic nucleus. Electric field E_N and interaction with nuclear EDM $d_N E_N$ are nonzero. Schiff 1963
- Atomic EDM $d_A=10^{-7}Z M_N d_N$

  M_N is nuclear magnetic moment in nuclear magnetons.

  Porsev, Ginges and V.F.   PRA 83, 042507, 2011

  This mechanism is important in light atoms and molecules only, since effect of Schiff moment increases faster than Z^2

  Compare to proposals of measurements of nuclear (proton) EDM at accelerators

Magnetic quadrupole moment.

- Nuclear MQM Khriplovich 1976, Haxton, Henley 1983
- Magnetic quadrupole moments (MQM) produce EDM in atoms and molecules

Magnetic interaction is not screened! Effect may be bigger than that of Schiff moment, generically ~10 times

Sushkov, Flambaum, Khriplovich 1984

Atomic EDMs

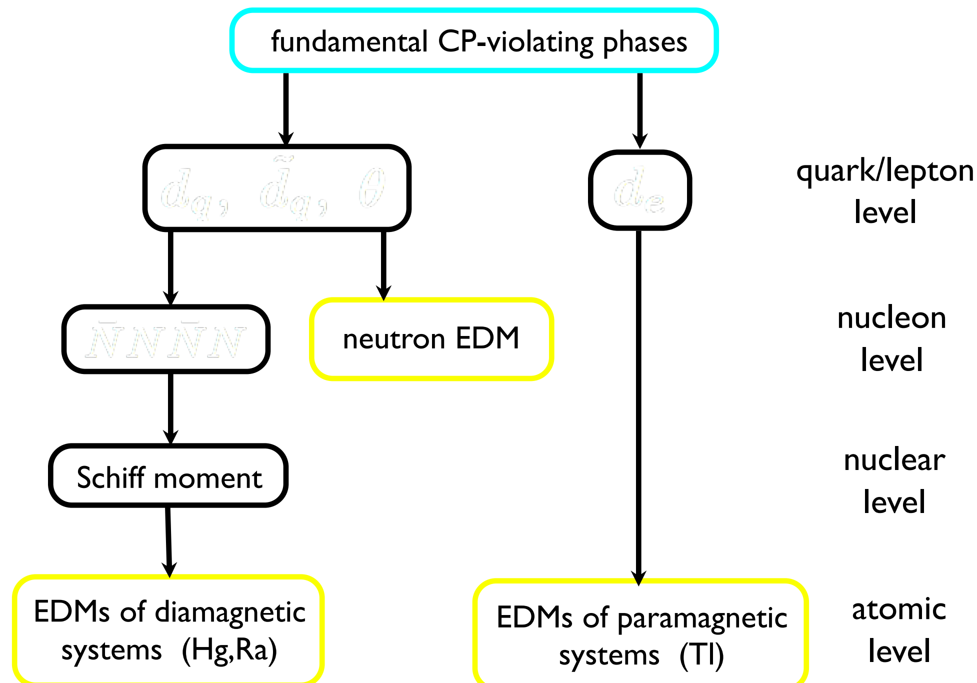
Atomic limits

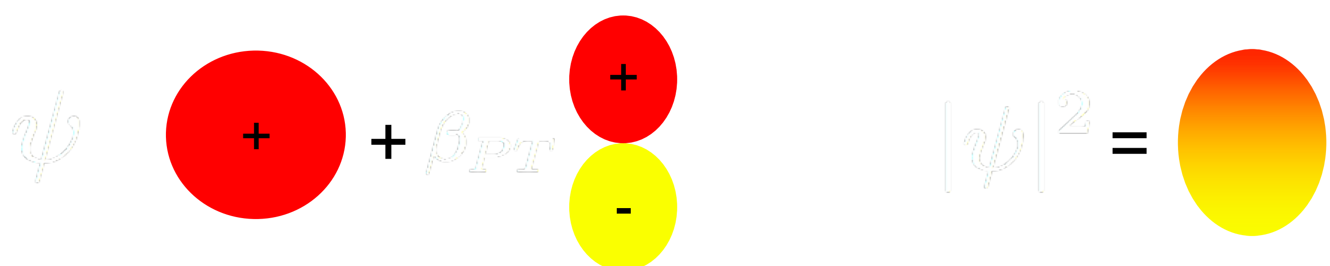
|$d(^{199}\text{Hg})$| Seattle

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

|d(n)| Grenoble, PINP, PSI

Leading mechanisms for EDM generation





Collective magnetic quadrupole moment

MQM produced by nuclear T,P-odd forces

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

V.F. 1994

Nuclear and molecular calculations of MQM effects

Nuclear and molecular estimates for

TaN, ThO, BaF, HgF, YbF, HfF+ V.F. , DeMille, Kozlov 2014

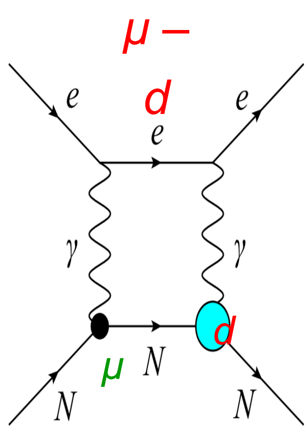
(TaO+, WN+)

Accurate molecular calculations

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

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.
- Nuclear spin may be zero as in electron EDM experiments



Internal nuclear excitations

	^{232}ThO	^{180}HfF^{+}
$\|C_{SP}\|$	7.3×10^{-10} [31]	1.8×10^{-8} [29, 53]
$\|d_p\|$	$1.1\times10^{-23}e\cdot$cm	$1.5\times10^{-22}e\cdot$cm
$\|d_n\|$	$1.0\times10^{-23}e\cdot$cm	$2.0\times10^{-22}e\cdot$cm
$\|\bar{g}^{(0)}_{\pi NN}\|$	3.1×10^{-10}	5.6×10^{-9}
$\|\bar{g}^{(1)}_{\pi NN}\|$	3.3×10^{-10}	8.2×10^{-9}
$\|\tilde{d}_d\|$	9.3×10^{-25}cm	2.2×10^{-23}cm
$\|\tilde{d}_u\|$	1.7×10^{-24}cm	5.8×10^{-23}cm
$\|\bar{\theta}\|$	1.4×10^{-8}	2.7×10^{-7}

$\frac{\|\xi_p\|}{10^{-23}\text{cm}}$	$\frac{\|\xi_n\|}{10^{-23}\text{cm}}$	$\frac{\bar{g}^{(0)}_{\pi NN}}{10^{-9}}$	$\frac{\bar{g}^{(1)}_{\pi NN}}{10^{-9}}$	$\frac{\bar{g}^{(2)}_{\pi NN}}{10^{-9}}$	$\frac{\tilde{d}_u}{10^{-24}\text{cm}}$	$\frac{\tilde{d}_d}{10^{-24}\text{cm}}$	$\frac{\bar{\theta}}{10^{-8}}$
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 $|C_{SP}| < 7.3\times10^{-10}$.

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

$\varphi(\mathbf{R})$ in multipole expansion is reduced to

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

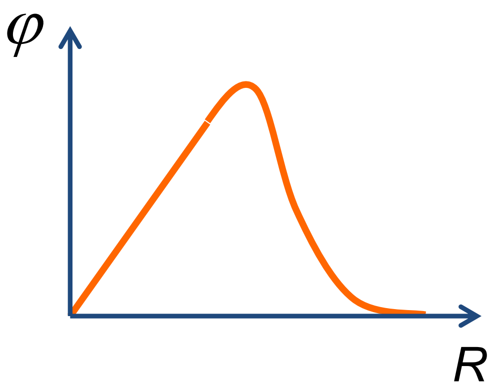
where $\mathbf{S} = \frac{e}{10}\left[\langle r^2\mathbf{r}\rangle - \frac{5}{3Z}\langle r^2\rangle\langle\mathbf{r}\rangle\right]$ is Schiff moment.

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

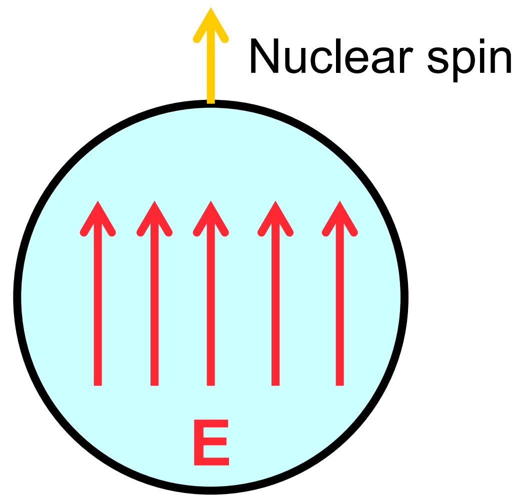
Atomic EDM is proportional to Z^2 x Relativistic factor, which is infinite for the point-like nucleus

Flambaum, Ginges, 2002:

$$\varphi(\mathbf{R}) = -\frac{3\mathbf{S}\bullet\mathbf{R}}{B}\rho(R) \quad \text{where} \quad B = \int \rho(R) R^4 dR$$



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 $Z^2\alpha^2$ originating from electron wave functions can be incorporated into *Local Dipole Moment* (**L**)

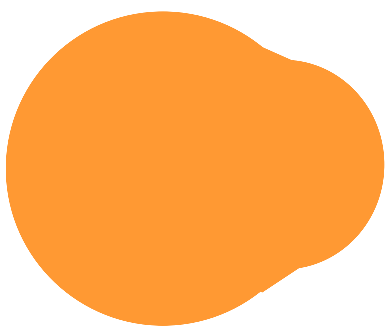
$$\mathbf{L} = \sum_{k=1}^{\infty} \mathbf{S}_k$$

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

Nuclear enhancement

Auerbach, Flambaum, Spevak 1996

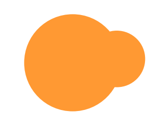
The strongest enhancement is due to octupole deformation (Rn,Ra,Fr,…)



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 

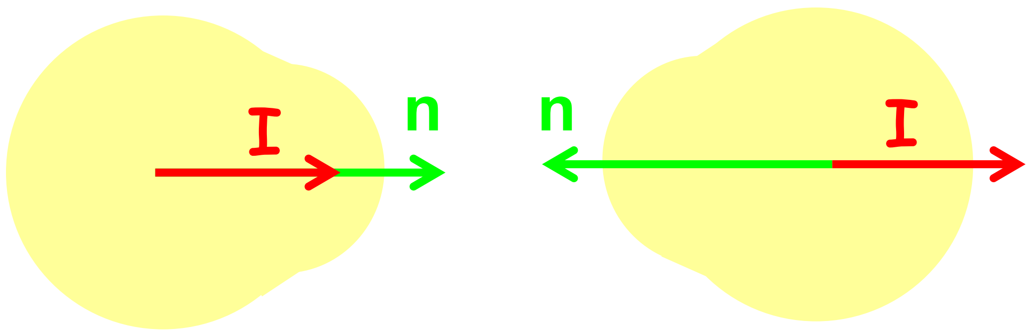
No T,P-odd forces are needed for the Schiff moment and EDM in intrinsic reference frame

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

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

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>

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

^{225}Ra, ^{223}Rn, Fr,… -100-1000 times enhancement
Results are stable – screening term is small, no cancellation

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

EDMs of atoms of experimental interest

Z	Atom	[S/(e fm3)]e cm	[10^{-25} η] 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 Heifei
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 $\eta = 0.3\ 10^{-8}$ $d_n = 5 \times 10^{-24}\ e$ cm η, $d(^{199}\mathrm{Hg})/\ d_n = 10^{-1}$

Limit from Hg EDM $\theta < 0.5\ 10^{-10}$ Seattle, V.F. and Dzuba, PRA101, 042504,2020

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, ^{155}Gd (stable), ^{229}Th (8 thousand years),

^{229}Pa (unstable but possibly huge SM due to very close nuclear level– 100 eV ?,

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

Effects of Schiff moment in molecules and solids

Enhancement due to strong internal electric field in polar molecules Sandars 1967

TIF experiments: Hinds et al, DeMille, T. Zelevinsky et al

Enhancement factors in Ra, Ac, Th, Np, Eu, … molecules

- Biggest Schiff moment
- Highest nuclear charge

  Largest T,P-odd nuclear spin-molecuar axis interaction κ(I n)

^{225}RaO= 200 TIF 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

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

Recent suggestions of experiments with solids to search for oscillating Schiff moment produced by axion dark matter: CASPEr Budker et al 2014, Piezoaxionic effect Arvanitaki et al 2021 Polarization haloscope Berlin, Zhou 2022

Enhancement of electron EDM

- Sandars: atomic EDM induced by interaction of electron EDM with atomic electric field increases as Z^{3}. Enhancement >100

Enhancement factor in atoms $3 Z Z^2\alpha^2 R(Z\alpha)$ V.F. 1976

Tl enhancement d(Tl)= -500 d_e . Many new calculations.

Tl experiment – Berkeley;

Cs, Fr, Xe*,

- Molecules –close rotational levels, huge enhancement of electron EDM:
- $Z^3 \alpha^2 R(Z\alpha) M/m_e$ Sushkov , Flambaum 1978 .

Ω =1/2 10^7 YbF London

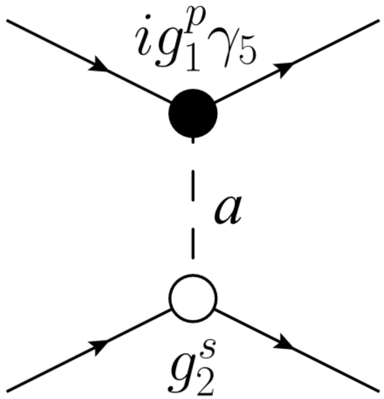
Ω=1 10^{10} PbO,ThO Yale, Harvard

HfF^+ ThF+ Boulder YbOH

Weak electric field is sufficient to polarise the molecule. Molecular electric field is several orders of magnitude larger than external field (Sandars). Accurate calculations by several groups

ThO : dramatic improvement 100 times! HfF+ JILA higher accuracy

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

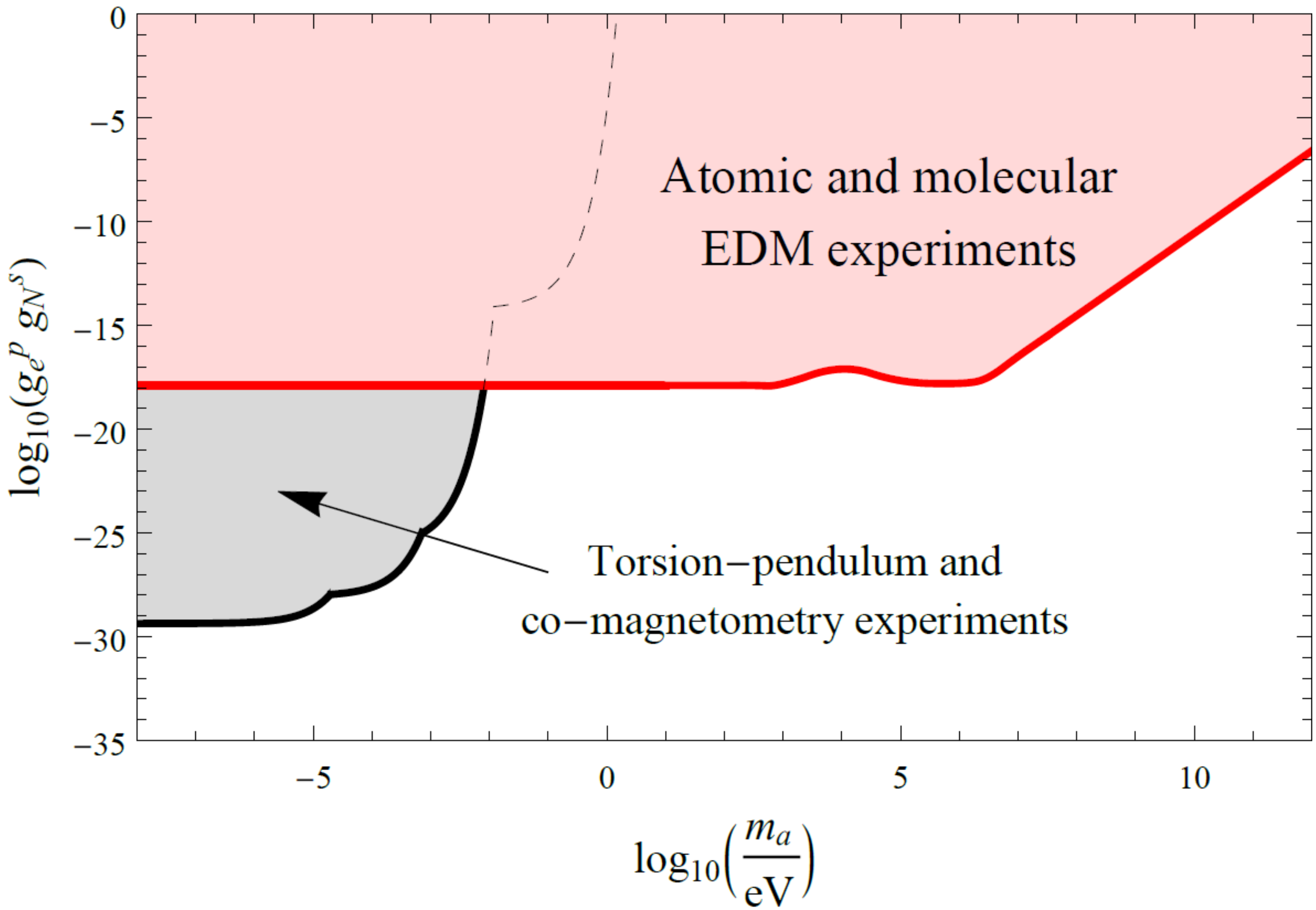
Molecular EDM experiments: YbF, HfF^+, ThO

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

- *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 $\langle\rho_\varphi\rangle \approx m_\varphi^2 \varphi_0^2/2$ ($\rho_{\mathrm{DM,local}} \approx 0.4\ \mathrm{GeV/cm^3}$)
- 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

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

Classical field

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

Low-mass Spin-0 Dark Matter

Dark Matter

Scalars (or squared axion field φ^2):

$\varphi^n \rightarrow +\varphi^n$

$\rightarrow$ Time-varying fundamental constants

10^{15} improvement

Pseudoscalars (Axions):

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

$\rightarrow$ Time-varying spin-dependent effects, EDM and other T,P-violating moments

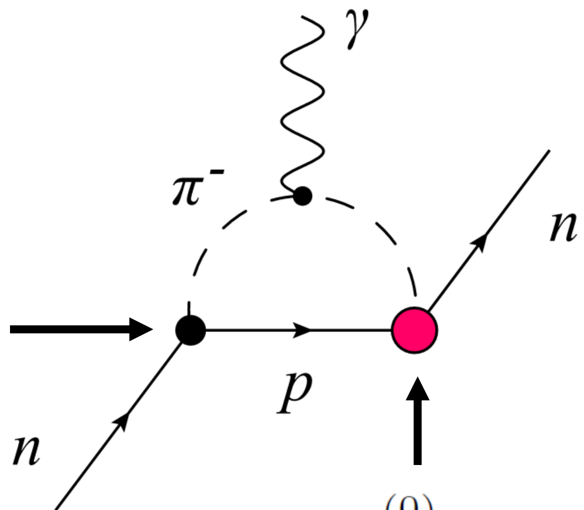
10^{3} improvement

Axion-Induced Oscillating Neutron EDM

[Crewther, Di Vecchia, Veneziano, Witten, *PLB* 88, 123 (1979)], [Pospelov, Ritz, *PRL* 83, 2526 (1999)], neutron EDM due to QCD theta

[Graham, Rajendran, *PRD* 84, 055013 (2011)] theta(t)=a(t)/f_a , a(t) is axion field

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



$g_{\pi NN} = 13.5$

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

Axion-Induced Oscillating Atomic and Molecular EDMs

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

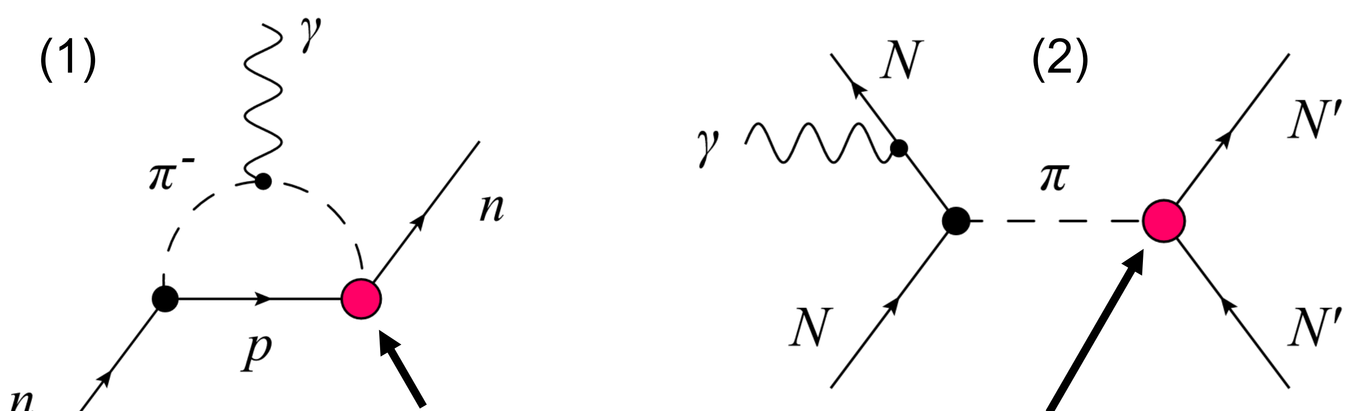
Induced through *hadronic mechanisms*:

- Oscillating nuclear Schiff moments ($I \geq 1/2$ => $J \geq 0$)
- Oscillating nuclear magnetic quadrupole moments ($I \geq 1$ => $J \geq 1/2$; *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)

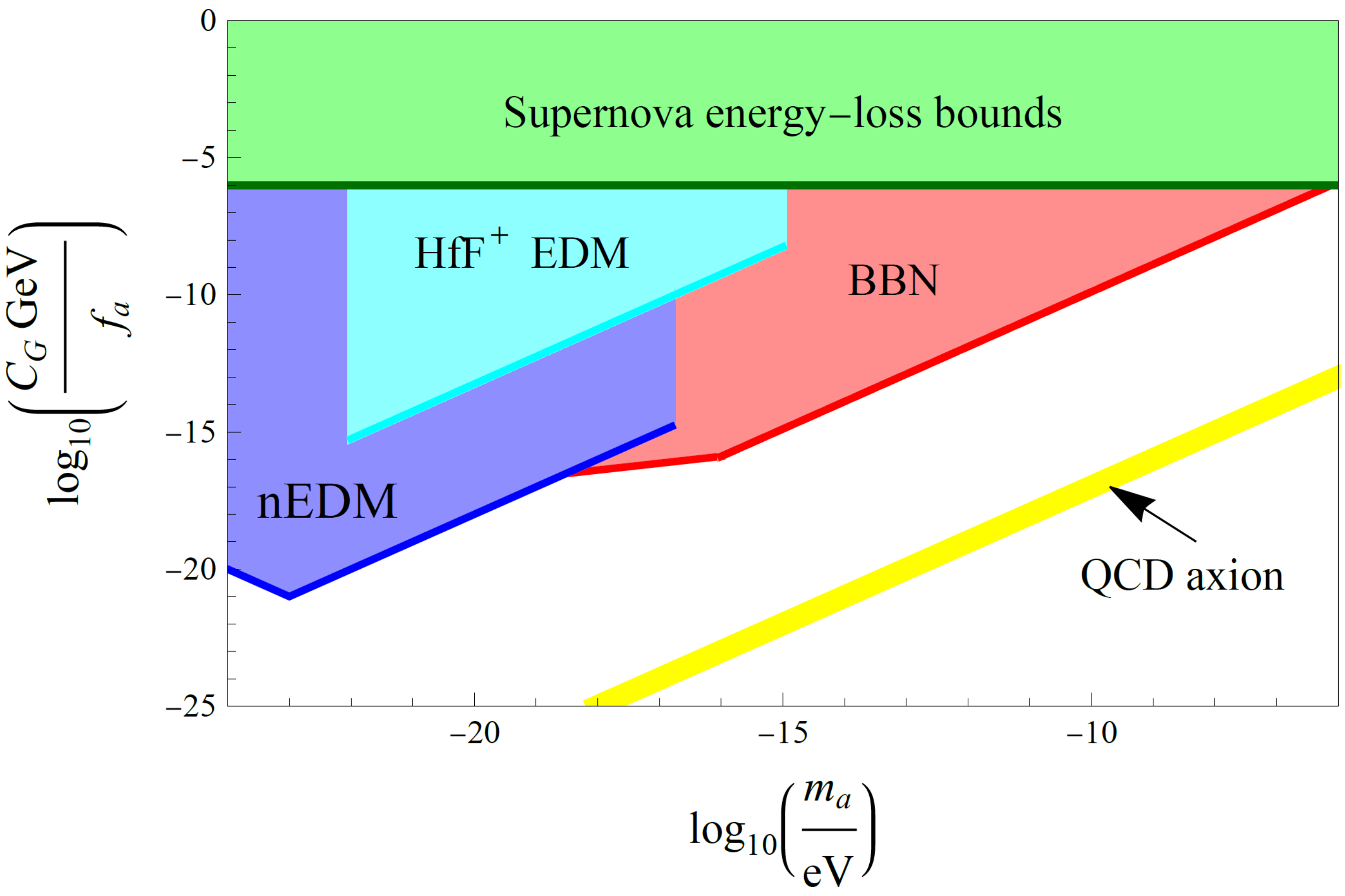


$$\bar{g}^{(0)}_{\pi NN} \approx 0.016\ C_G a_0 \cos(m_a t)/f_a$$

Constraints on Interaction of Axion Dark Matter with Gluons

nEDM constraints: [nEDM collaboration, *PRX* **7**, 041034 (2017)]

HfF^+ EDM constraints: [Roussy *et al*., *PRL* **126**, 171301 (2021)]



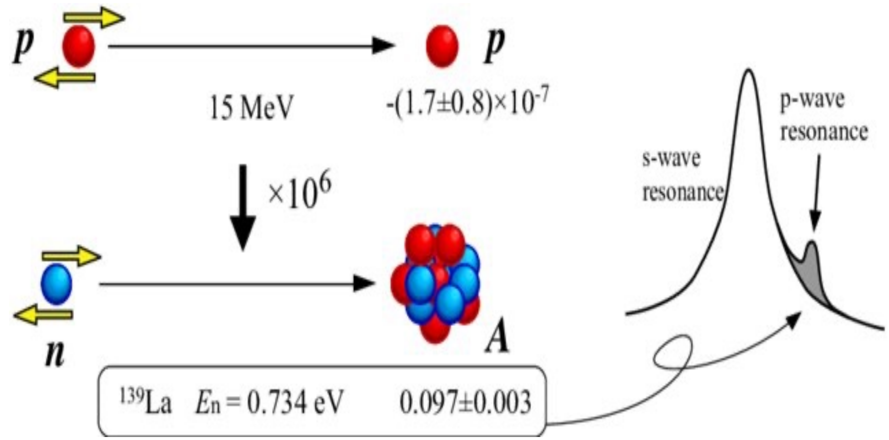
OSCILLATING NUCLEAR ELECTRIC DIPOLE, MAGNETIC QUADRUPOLE AND SCHIFF MOMENTS, INDUCED BY AXIONIC DARK MATTER, PRODUCE MOLECULEAR TRANSITIONS

M2 transition: photon suppressed, axion is not suppressed!

Smaller systematics

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

10^6 enhancement of Parity and Time-reversal violation in neutron reactions near p-wave compound resonances



$$P = 2\sum_s \frac{iW_{sp}}{E_s - E_p}\sqrt{\frac{\Gamma_s^n}{\Gamma_p^n}}$$

$$W_{sp} = \langle s|W|p\rangle$$

$$\frac{1}{E_s - E_p} \sim 10^3$$

$$\sqrt{\frac{\Gamma_s^n}{\Gamma_p^n}} \sim 10^3$$

$$\Longrightarrow\ P \text{ enhanced by up to} \sim 10^6$$

P-odd Sushkov and Flambaum, 1980.
T,P-odd Bunakov and Gudkov 1983
P-odd confirmed by numerous experiments
T,P-odd several experiments in Japan and USA

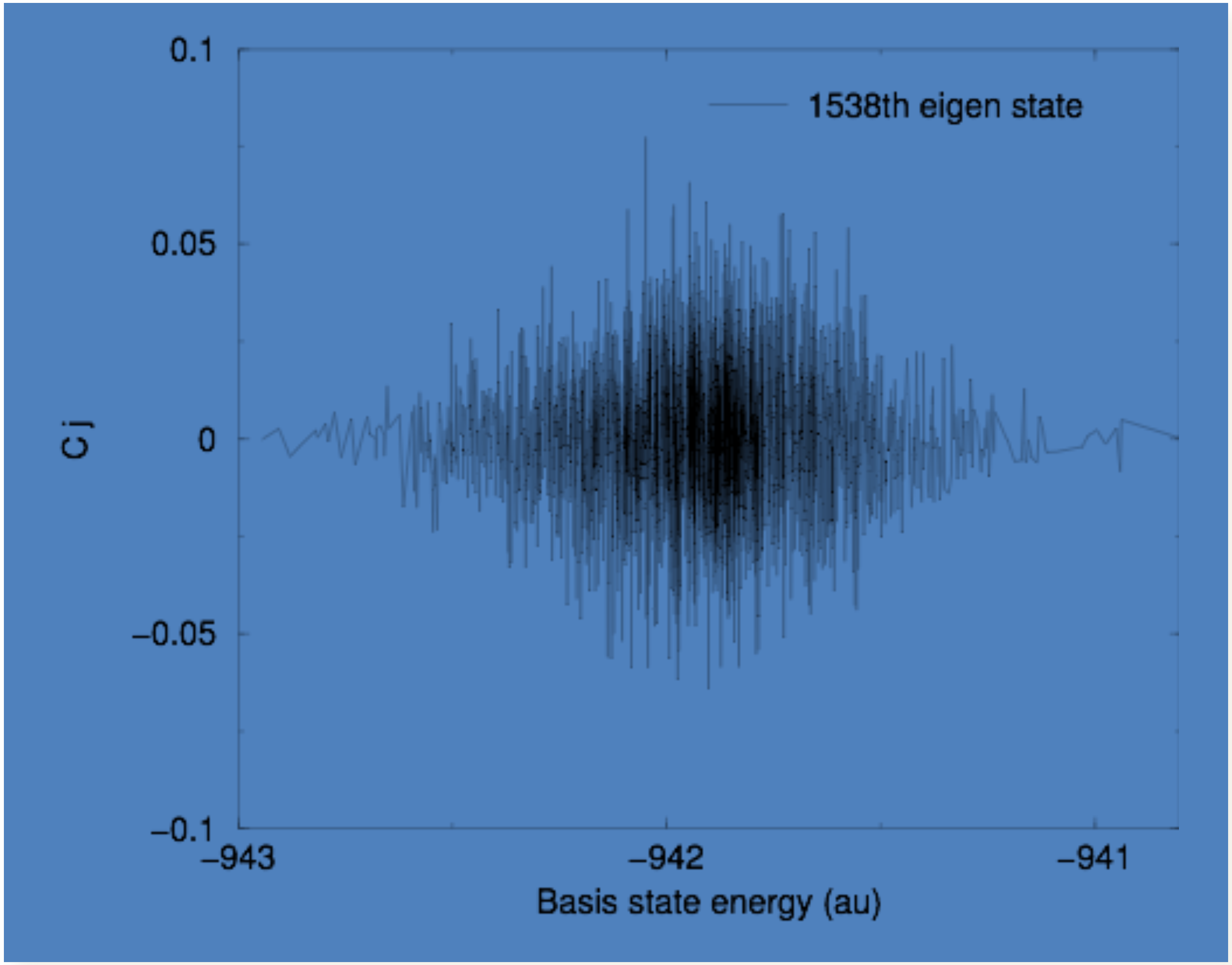
Typical eigenstate in excited Au^{24+}

Graph shows eigen-state components

$$|\Psi_\nu\rangle = \sum_j C_j^{(\nu)} |\Phi_j\rangle$$

as a function of the basis-state energies

$$E_j = \langle \Phi_j | H | \Phi_j \rangle$$



- Components fluctuate (are uncorrelated - "quantum chaos"). Random variables, $\langle C_j \rangle = 0$
- Breit-Wigner type dependence of $\langle C_j^2 \rangle$ on $E_j - E_\nu$

Statistical theory based on properties of chaotic eigenstates

- Theory predicts matrix elements between chaotic states: Orbital occupation numbers, magnetic moments, electromagnetic amplitudes, enhancement of weak interactions and recombination, increase of entropy, etc. Accurate predictions, tested!
- Similar to gas in this room: we do not know motion of each molecule but can very accurately predict occupation numbers, distribution of velocities, pressure, etc.
- We calculated P-odd and T,P-odd matrix elements between chaotic nuclear compound states. Due to the million times enhancements, the measurements should improve limits on T,P-odd interactions by an order of magnitude or more.

V.F. 1992, V.F. and Vorov 1993-1995, Fadeev and V.F 2020, V.F. and Mansour 2022.

Summary

Schiff moment is enhanced up to 1000 times in nuclei with octupole deformation → radioactive molecules RaO, AcN, ThO, Np ,… Stable EuN ? Experiments with solids. Nuclear spin *I* ≥ ½

Limit from Hg EDM: $\theta < 0.5\ 10^{-10}$

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 in non-stationary states or 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

10^6 enhancement of P-odd and P,T-odd effects in neutron reactions near p-wave nuclear compound resonances

Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

Consider an oscillating classical *scalar* or axion field, $\varphi(t) = \varphi_0 \cos(m_\varphi t)$, that interacts with SM fields (e.g. a fermion *f*) via <u>*quadratic couplings*</u> in φ.

$$\mathcal{L}_f = -\frac{\phi^2}{(\Lambda'_f)^2} m_f \bar{f} f \quad \text{c.f.} \quad \mathcal{L}_f^{\text{SM}} = -m_f \bar{f} f \quad => \quad m_f \to m_f \left[1 + \frac{\phi^2}{(\Lambda'_f)^2} \right]$$

$$=> \frac{\delta m_f}{m_f} = \frac{\phi_0^2}{(\Lambda'_f)^2} \cos^2(m_\phi t) = \boxed{\frac{\phi_0^2}{2(\Lambda'_f)^2}} + \boxed{\frac{\phi_0^2}{2(\Lambda'_f)^2} \cos(2 m_\phi t)}$$

‘Slow’ drifts [Astrophysics (high ρ_{DM}): BBN, CMB]

Oscillating variations [Laboratory (high precision)]

Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

[Stadnik, and V.F. *PRL* 114, 161301 (2015); *PRL* 115, 201301 (2015)]

<u>Fermions:</u>

$$\mathcal{L}_f = -\frac{\phi^2}{(\Lambda'_f)^2} m_f \bar{f} f \quad => m_f \to m_f \left[1 + \frac{\phi^2}{(\Lambda'_f)^2} \right]$$

<u>Photon:</u>

$$\mathcal{L}_\gamma = \frac{\phi^2}{(\Lambda'_\gamma)^2} \frac{F_{\mu\nu} F^{\mu\nu}}{4} \quad => \alpha \to \frac{\alpha}{1 - \phi^2/(\Lambda'_\gamma)^2} \simeq \alpha \left[1 + \frac{\phi^2}{(\Lambda'_\gamma)^2} \right]$$

<u>*W* and *Z* Bosons:</u>

$$\mathcal{L}_V = \frac{\phi^2}{(\Lambda'_V)^2} \frac{M_V^2}{2} V_\nu V^\nu \quad => M_V^2 \to M_V^2 \left[1 + \frac{\phi^2}{(\Lambda'_V)^2} \right]$$

Astrophysical Constraints on 'Slow' Drifts in Fundamental Constants Induced by Scalar Dark Matter (BBN)

[Stadnik, Flambaum, *PRL* **115**, 201301 (2015)]

- Largest effects of scalar dark matter are in the early Universe (highest ρ_{DM} => highest φ_0^2).
- Earliest cosmological epoch that we can probe is Big Bang nucleosynthesis (from $t_{weak} \approx$ 1s until $t_{BBN} \approx$ 3 min).
- Primordial ^{4}He abundance is sensitive to relative abundance of neutrons to protons (almost all neutrons are bound in ^{4}He by the end of BBN).

Weak interactions: freeze-out of weak interactions occurs at $t_{weak} \approx$ 1s ($T_{weak} \approx$ 0.75 MeV).

$$p + e^- \rightleftharpoons n + \nu \qquad \left(\frac{n}{p}\right)_{\text{weak}} = e^{-(m_n - m_p)/T_{\text{weak}}}$$
$$n + e^+ \rightleftharpoons p + \bar{\nu}$$

We performed atomic (Dzuba et al) and nuclear calculations to link change of transition frequencies to change of constants:

Optical transitions: atomic calculations for quasar absorption spectra and for atomic clocks

$\omega = \omega_0 + q(\alpha^2/\alpha_0^2 - 1), \quad \delta\omega/\omega = K\, \delta\alpha/\alpha$

Molecular transitions

Microwave transitions

Mossbauer transitions

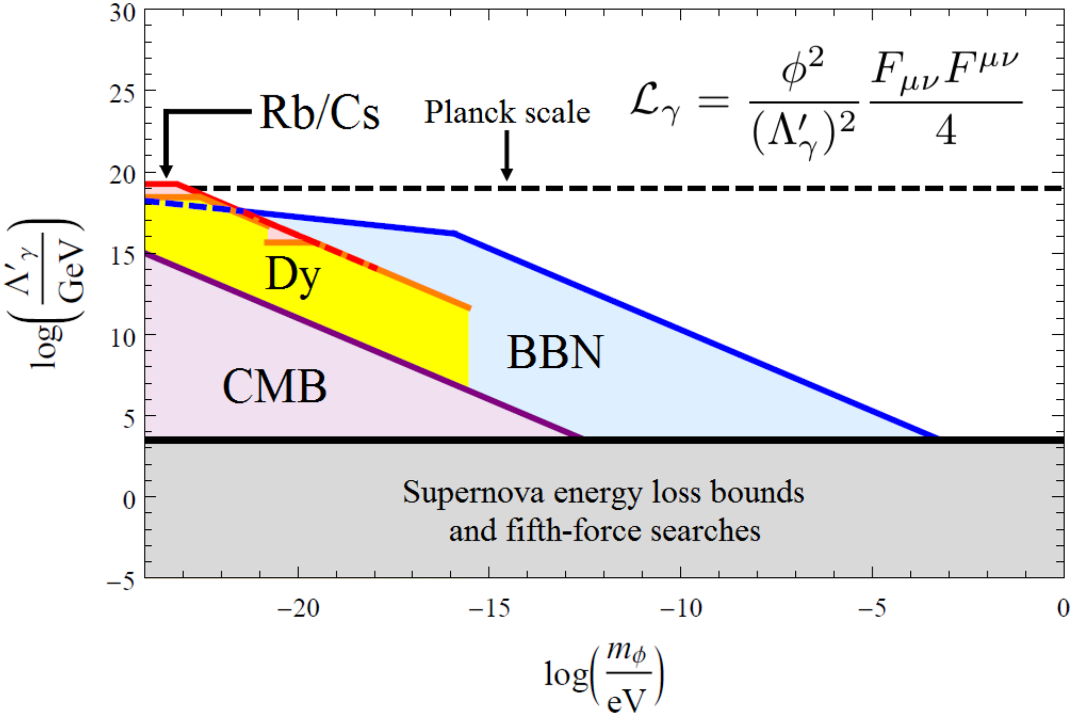
<u>^{229}Th nuclear clock are most sensitive to variation of the fundamenatal constants</u>

Constraints on Quadratic Interaction of Scalar Dark Matter with the Photon

BBN, CMB, Dy and Rb/Cs constraints:

[Stadnik and V.F., *PRL* **115**, 201301 (2015) + Phys. Rev. D 2016]

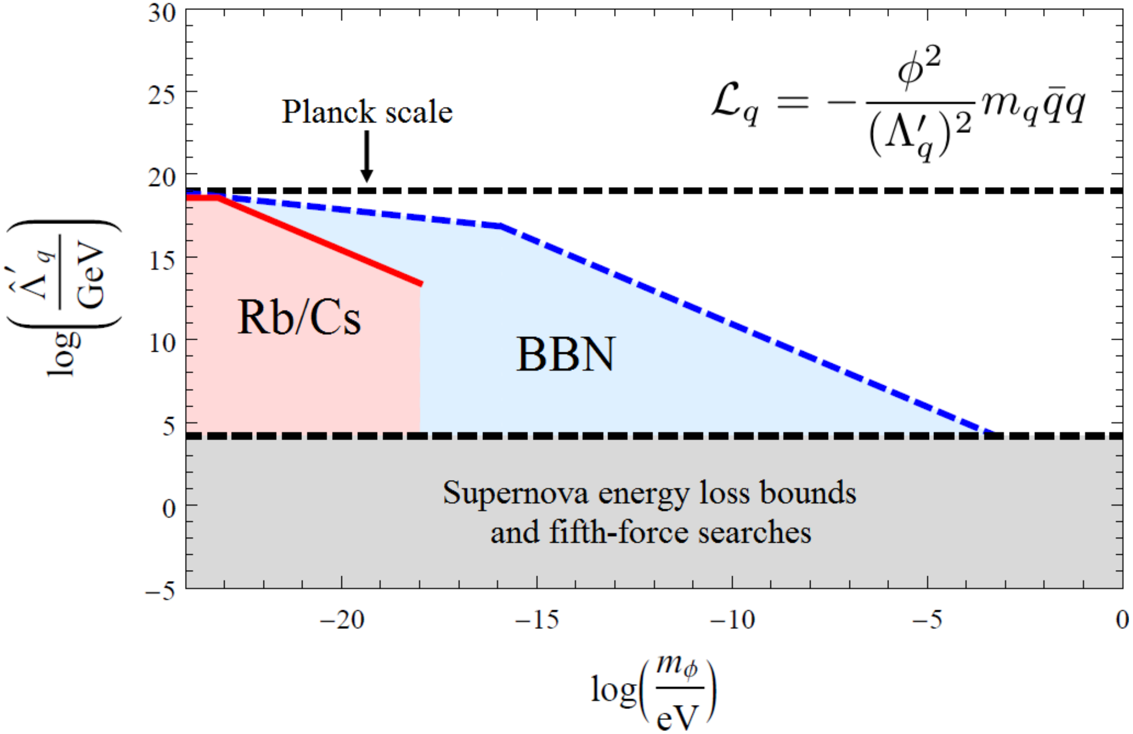
15 orders of magnitude improvement!



Constraints on Quadratic Interactions of Scalar and Axion Dark Matter with Light Quarks

BBN and Rb/Cs constraints:

[Stadnik and V.F., *PRL* **115**, 201301 (2015) + Phys. Rev. D 2016]



Mechanism generating quadratic dependence on axion field: pion mass depends on $\theta^2=(a/f_a)^2$

Ubaldi 2010 ; Kim, Perez 2022

Nuclear magnetic moments, mass and radius depend on pion mass.

V.F. and Tedesco 2006, V.F. and Wiringa 2007, 2009,

Effects in hyperfine transitions in Cs and Rb. Measurements Guena et al 2012, Hees et al 2016. Pion- axion interpretation Kim, Perez 2022

Recently measured effect of variation of nuclear radius in optical atomic transitions in Yb+, Banerjee et al 2023. New limits in V.F. and Mansour 2023

Averaging over fast oscillations (frequency=m_a) allows one to measure 10^6 times slower fluctuations of the scalar and axion dark matter density and extend covered interval of dark matter particle masses. Masia –Roig et al 2022.
New limits in V.F. and Samsonov 2023