Low-mass Spin-0 Dark Matter

Dark Matter

Scalars

(or squared axion field φ^2):

$\varphi^n \longrightarrow +\varphi^n$

$\longrightarrow$ Time-varying fundamental constants

10^{15} improvement

Pseudoscalars

(Axions):

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

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

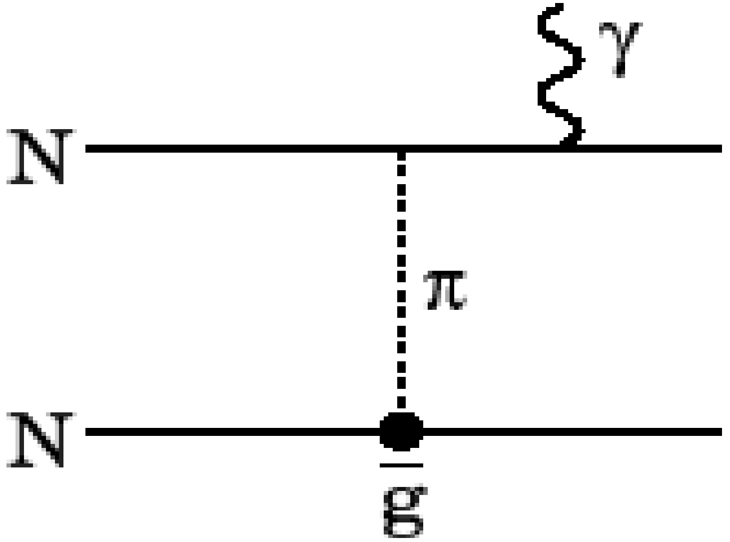
10^3 improvement

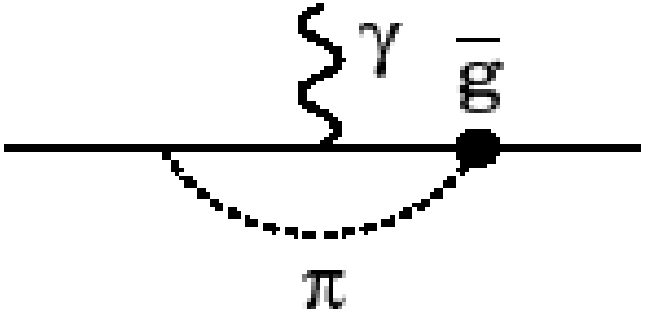
Nuclear T,P-violating moments induce atomic and molecular EDM

Victor Flambaum

Co-authors: I.Khriplovich, O.Sushkov, V.Dzuba, N.Auerbach, Spevak, J.Ginges, M.Kozlov, D. DeMille, S.Porsev, J. Berengut, Y. Stadnik, Y, L. Skripnikov, A. Petrov, A. Titov, H. Feldmeier, H.B. Tran Tan, I. Samsonov, M. Pospelov, A. Ritz, O. Vorov, P. Fadeev, A. Mansour, ...

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:

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

$Z_i =0 \rightarrow E_N= 0$

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):

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

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

φ(**R**) in multipole expansion is reduced to

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

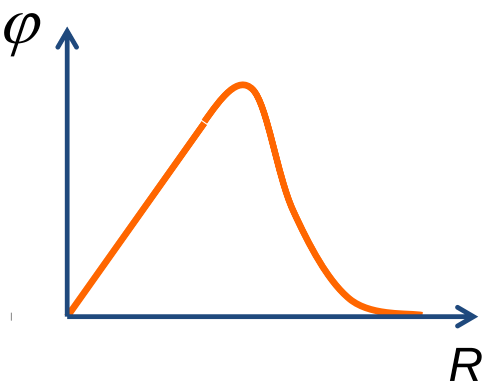
where $\mathbf{S} = \frac{e}{10}\left[\langle r^2 \mathbf{r}\rangle - \frac{5}{3Z}\langle r^2\rangle\langle \mathbf{r}\rangle\right]$ is Schiff moment.

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

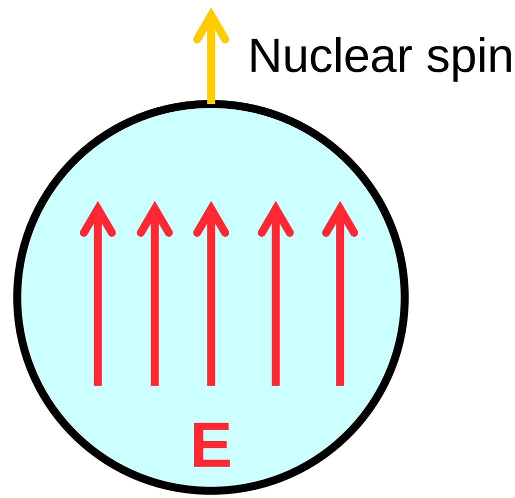
Atomic EDM is proportional to Z^2 x Relativistic factor, which is infinite for the point-like nucleus

Flambaum, Ginges, 2002:

$$\varphi(\mathbf{R}) = -\frac{3\mathbf{S}\bullet\mathbf{R}}{B}\rho(R)$$ 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 $Z^2\alpha^2$ originating from electron wave functions can be incorporated into *Local Dipole Moment* (**L**)

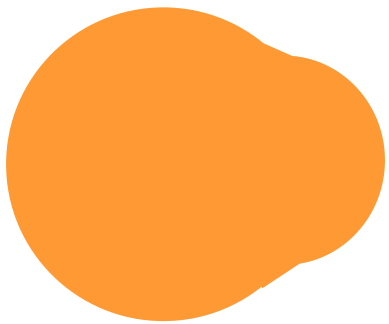
$$\mathbf{L} = \sum_{k=1}^{\infty} \mathbf{S}_k$$

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

Nuclear enhancement

Auerbach, Flambaum, Spevak 1996

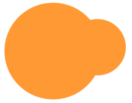
The strongest enhancement is due to octupole deformation (Rn,Ra,Fr,…)



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 

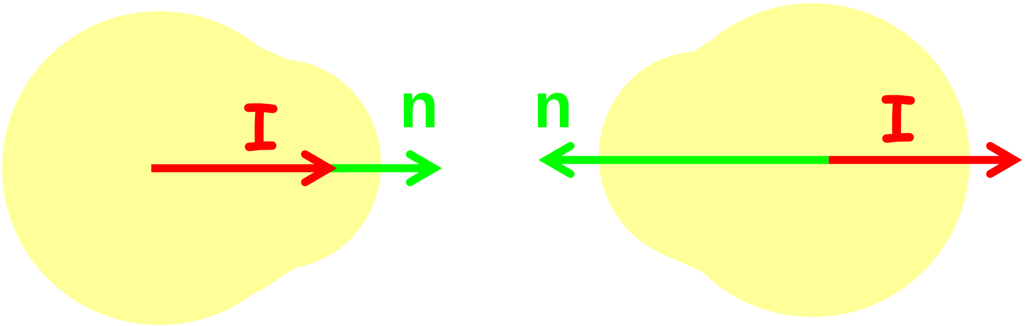
No T,P-odd forces are needed for the Schiff moment and EDM in intrinsic reference frame

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	[$S/(e\ fm^3)$]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 $\eta = 0.3\ 10^{-8}$ $d_n = 5 \times 10^{-24}\ e$ cm η, $d(^{199}\text{Hg})/d_n = 10^{-1}$

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

TlF 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 $\kappa(I\ n)$

^{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

^{227}AcN=^{227}AcO^{+} =400 TlF 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

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

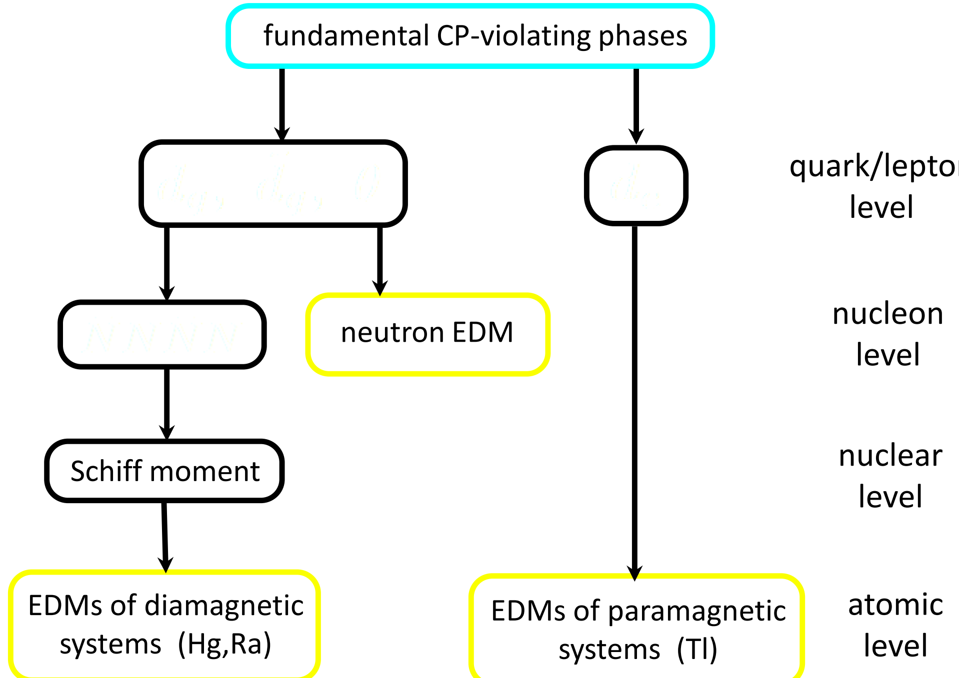
Atomic limits

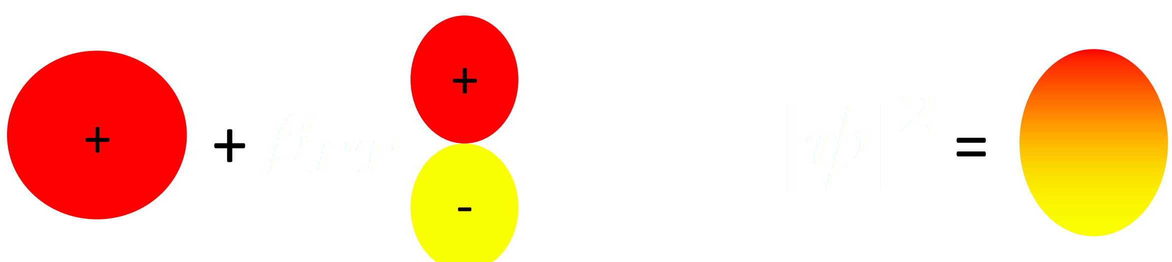
$|d(^{199}Hg)|$ Seattle

$|d(^{205}Tl)| < 9.6 \times 10^{-25}$ *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

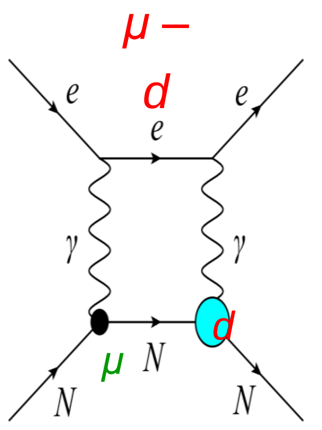
(TaO+, WN+)

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]
$\|d_p\|$	$1.1\times10^{-23} e\cdot\text{cm}$	$1.5\times10^{-22} e\cdot\text{cm}$
$\|d_n\|$	$1.0\times10^{-23} e\cdot\text{cm}$	$2.0\times10^{-22} e\cdot\text{cm}$
$\|\bar{g}^{(0)}_{\pi NN}\|$	3.1×10^{-10}	5.6×10^{-9}
$\|\bar{g}^{(1)}_{\pi NN}\|$	3.3×10^{-10}	8.2×10^{-9}
$\|\tilde{d}_d\|$	$9.3\times10^{-25}\text{cm}$	$2.2\times10^{-23}\text{cm}$
$\|\tilde{d}_u\|$	$1.7\times10^{-24}\text{cm}$	$5.8\times10^{-23}\text{cm}$
$\|\bar{\theta}\|$	1.4×10^{-8}	2.7×10^{-7}

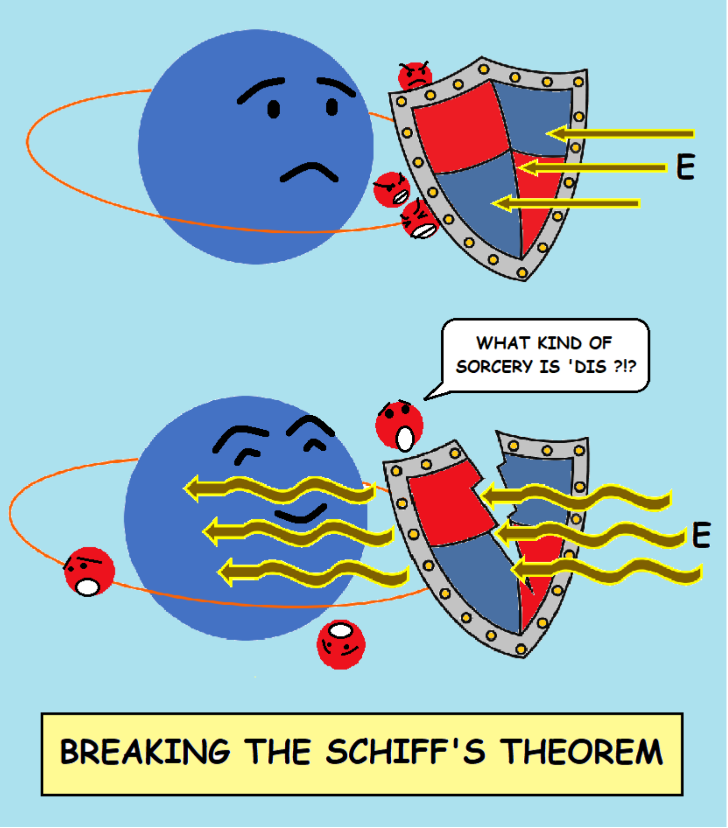
$\frac{\|\xi_p\|}{10^{-23}\text{cm}}$	$\frac{\|\xi_n\|}{10^{-23}\text{cm}}$	$\frac{\bar{g}^{(0)}_{\pi NN}}{10^{-9}}$	$\frac{\bar{g}^{(1)}_{\pi NN}}{10^{-9}}$	$\frac{\bar{g}^{(2)}_{\pi NN}}{10^{-9}}$	$\frac{\tilde{d}_u}{10^{-24}\text{cm}}$	$\frac{\tilde{d}_d}{10^{-24}\text{cm}}$	$\frac{\bar{\theta}}{10^{-8}}$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

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

$A = \varpi^2 D_z \times 5.14\ 10^9$ 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

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*,

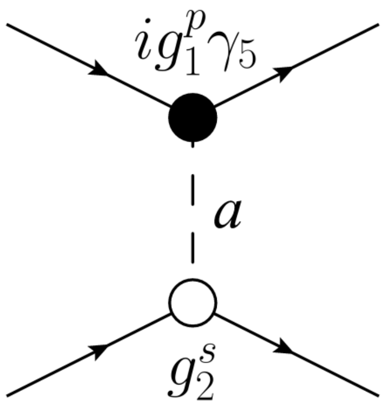
- Molecules –close rotational levels, huge enhancement of electron EDM:
- $Z^3 \alpha^2 R(Z\alpha)\, M/m_e$ Sushkov , Flambaum 1978 .

$\Omega = 1/2$	10^7	YbF	London
$\Omega = 1$	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

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

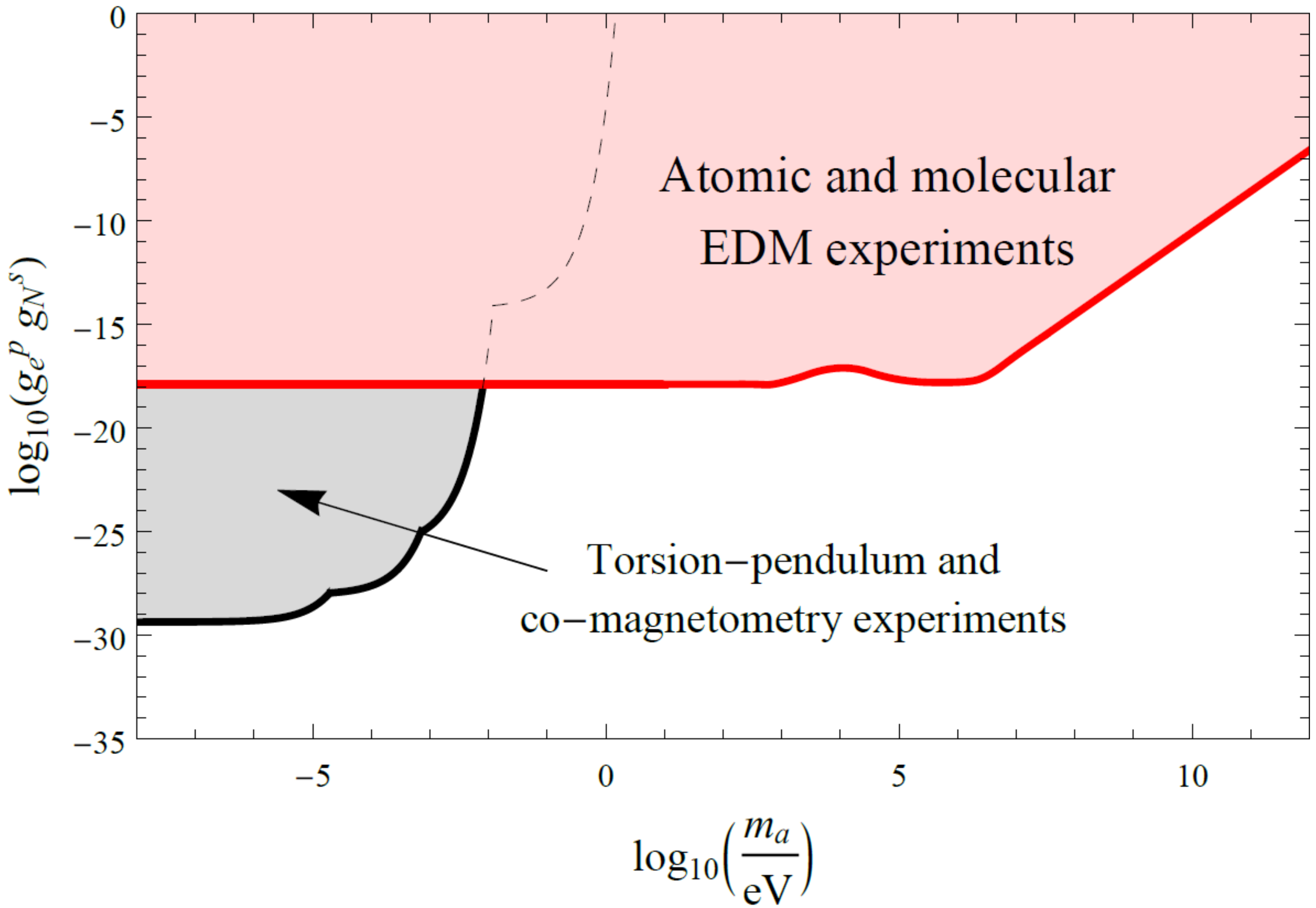
Molecular EDM experiments: YbF, HfF^+, ThO

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 $<\rho_\varphi> \approx m_\varphi^2 \varphi_0^2/2$ ($\rho_{\mathrm{DM,local}} \approx 0.4\ \mathrm{GeV/cm^3}$)
- Coherently oscillating field, since *cold* ($E_\varphi \approx m_\varphi c^2$)
- Classical field for $m_\varphi \leq 0.1$ eV, since $n_\varphi(\lambda_{\mathrm{dB},\varphi}/2\pi)^3 >> 1$
- 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

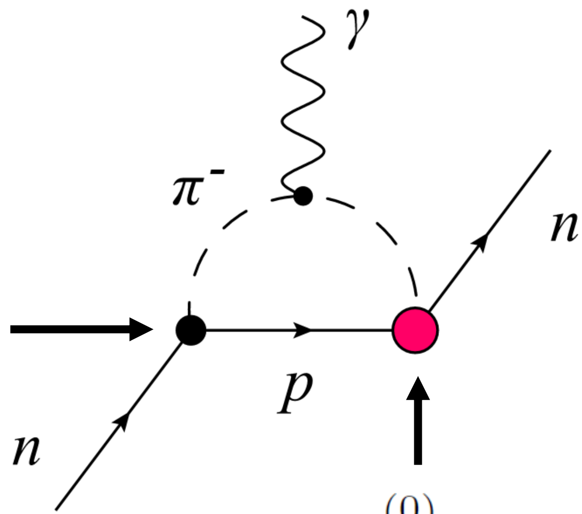
Axion-Induced Oscillating Neutron EDM

[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)]

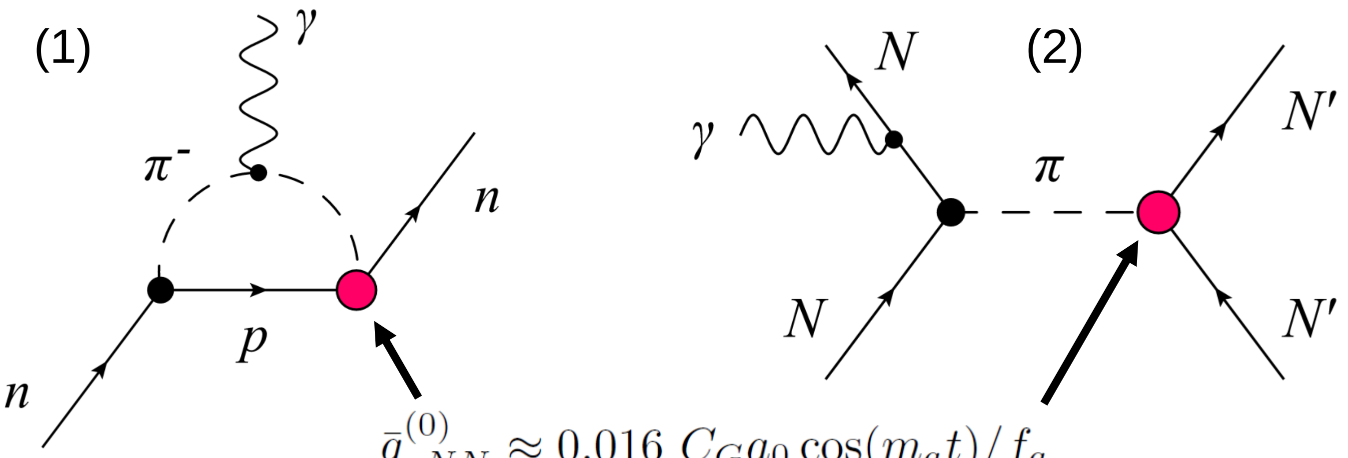
Induced through *hadronic mechanisms*:

- Oscillating nuclear Schiff moments ($I \geq 1/2 \Rightarrow J \geq 0$)
- 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 ~$4\pi^2 \approx 40$**; up to **extra 1000-fold enhancement** in deformed nuclei)

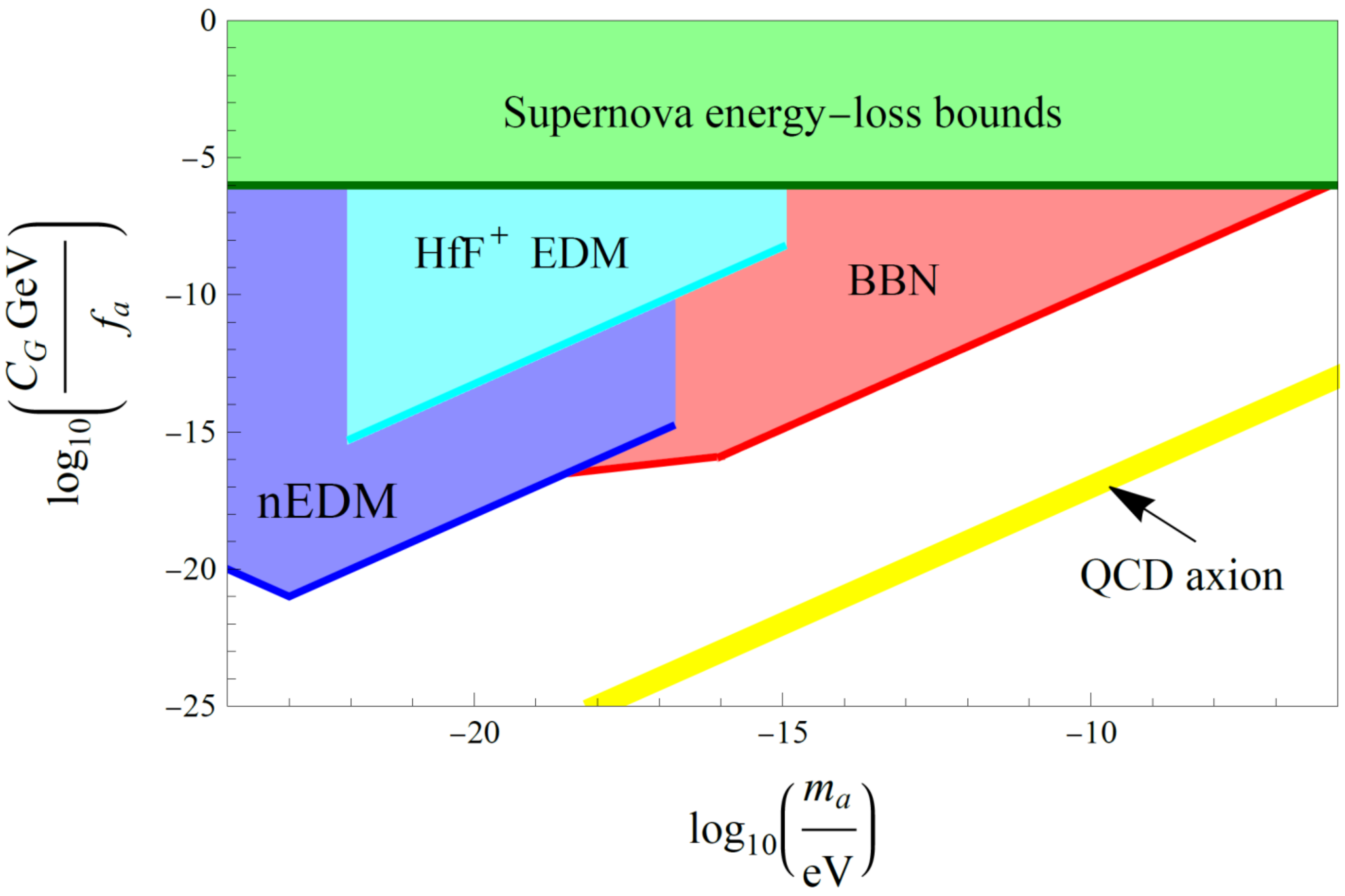


$$\bar{g}^{(0)}_{\pi NN} \approx 0.016\ C_G a_0 \cos(m_a t)/f_a$$

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)]



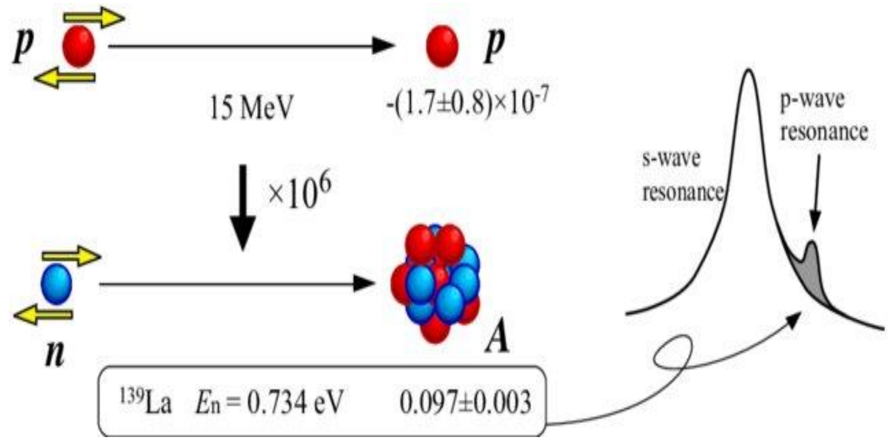
OSCILLATING NUCLEAR ELECTRIC DIPOLE, MAGNETIC QUADRUPOLE AND SCHIFF MOMENTS, INDUCED BY AXIONIC DARK MATTER, PRODUCE MOLECULEAR TRANSITIONS

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

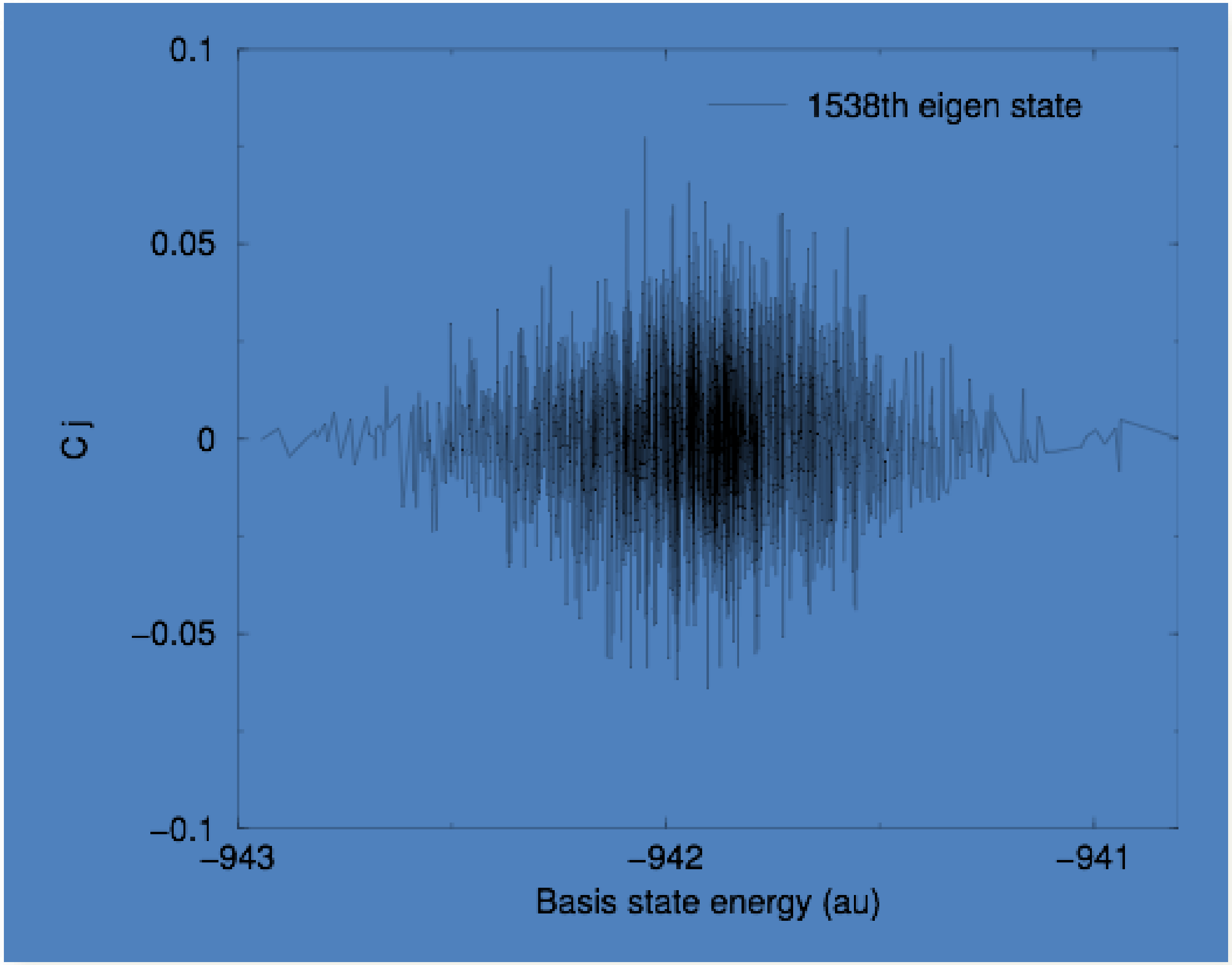
Typical eigenstate in excited Au^{24+}

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

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

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

Origin of chaotic eigenstates

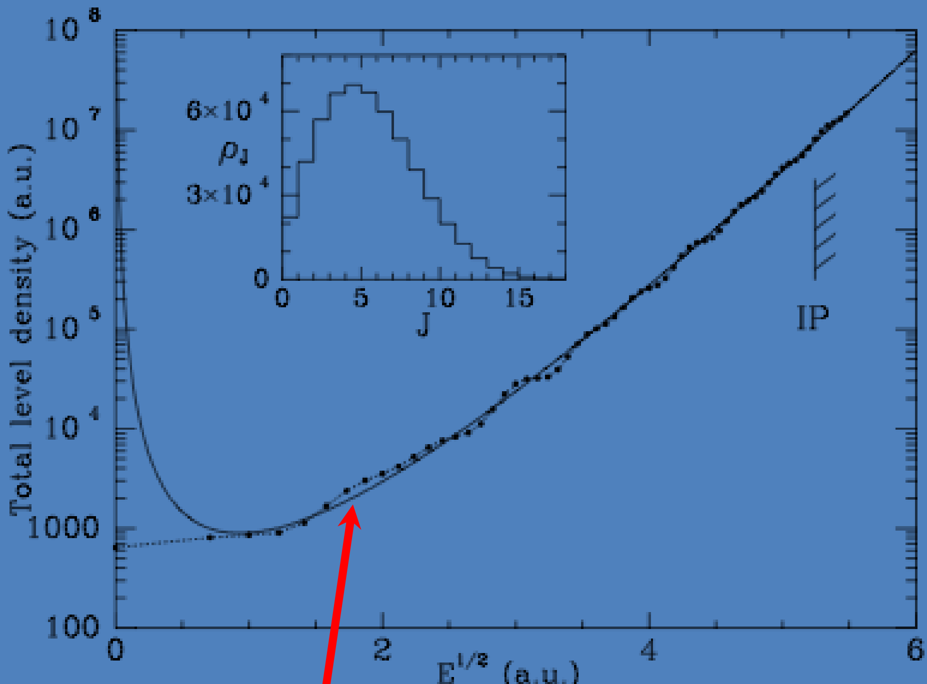
- Interval between energy levels in a system with many active particles is exponentially small (distribution of n particles over m orbitals gives exponentially large number of combinations m!/[n!(m-n)!] - millions!)
- Residual interaction between particles significantly exceeds this interval and mixes thousands of Hartree-Fock configurations into chaotic eigentstate

Many-excited-electron states in Au^{24+} and W^{+19}

Construction of the spectrum

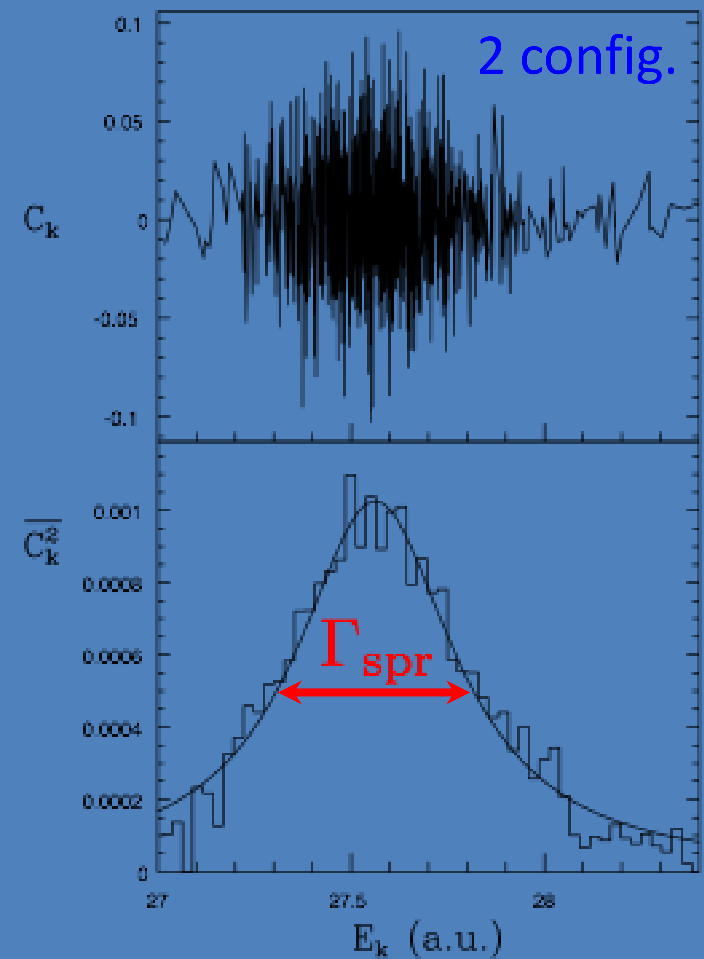
$$E_i = E_{core} + \sum_a \epsilon_a n_a + \sum_{a \le b} \frac{n_a(n_b - \delta_{ab})}{1 + \delta_{ab}} U_{ab} \,,$$

$$N_i = \prod_a \frac{g_a!}{n_a!(g_a - n_a)!} \,, \qquad g_a = 2j_a + 1$$



Fermi-gas ansatz $\rho(E) = AE^{-\nu} \exp(a\sqrt{E})$

Examining the eigenstates



$$\overline{C_k^2}(E) = \frac{1}{N} \frac{\Gamma_{spr}^2/4}{(E_k - E)^2 + \Gamma_{spr}^2/4}$$

Chaos! Calculation of matrix elements

<Compound state|M|Compound state>

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

Diagonal matrix elements contain $\langle C_i^2 \rangle$

$$C_k^2(E) = \frac{1}{N} \frac{\Gamma_{spr}^2/4}{(E_k - E)^2 + \Gamma_{spr}^2/4}$$

Average value of non-diagonal matrix elements is zero since $\langle C_i \rangle = 0$. Calculate product of matrix elements M^2 containing $\langle C_i^2 \rangle$. Calculation is reduced to sum of single-particle matrix elements times $\langle C_i^2 \rangle$

Effects of oscillating nuclear moments induced by axion

- Axion dark matter field is oscillating → **nuclear EDM, Schiff and magnetic quadrupole moment are oscillating**.
- Oscillating nuclear moments → oscillating atomic and molecular EDMs.
- **Large enhancement for molecules**.
- **Huge enhancement in resonance** → good for detection.
- Oscillating nuclear moments → Atomic & Molecular transitions.

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

Lorentz Invariance Violation in Coulomb Interaction

- V.F. and Romalis.PRL**118**,14250,2017 Anisotropy in the speed of light that has been constrained by Michelson-Morley-type experiments also generates anisotropy in the Coulomb interactions.

^{21}Ne data: Improvement by 10 orders of magnitude in comparison with previous experiments: the speed of light is isotropic to a part in 10^{28}.

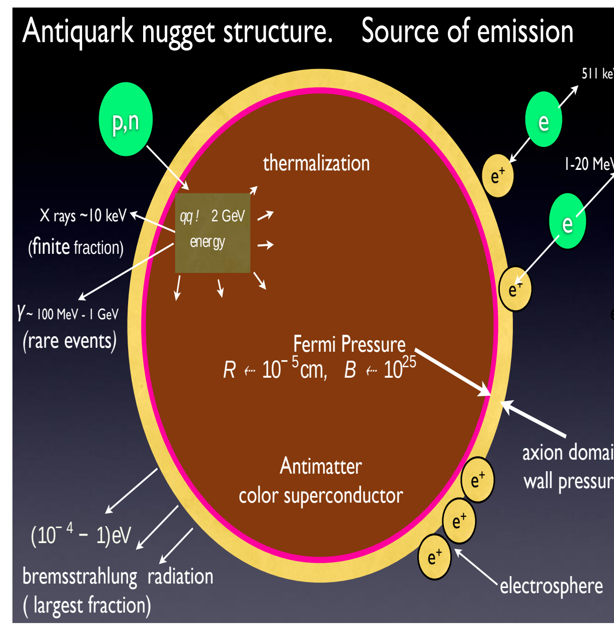
- V.F. PRL 2016: LLIV for proton improved by 4 orders of magnitude.

Q. G. Bailey and V. A. Kostelecký, Phys. Rev. D 70, 076006 (2004)

Axion-quark nuggets, QCD balls, Compact composite objects, etc.

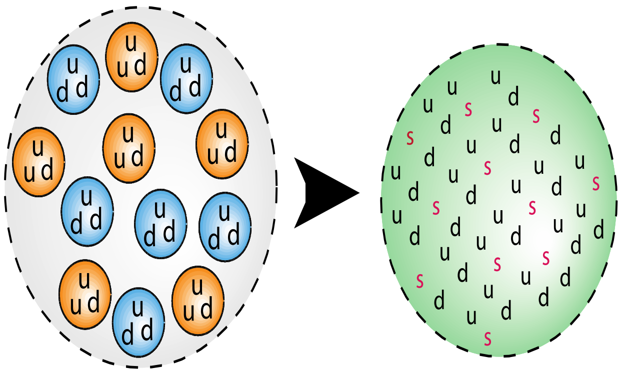
- Quark matter nuggets are composed of large number of quarks surrounded by electron cloud
- Anti-quark nugget consist of large number of anti-quarks, surrounded by the positron cloud
- Both quark and anti-quark nuggets amount to Dark Matter
- Assumption on ratio of abundances anti-quark nuggets : quark nuggets : baryonic matter = 3 : 2 : 1
- Explains matter-antimatter asymmetry in nature: anti-matter is hidden in anti-quark nuggets
- Has radiation which may (potentially) be detected

A. R. Zhitnitsky, JCAP10, 010 (2001)
And many subsequent papers



Adopted from the talk by A. Zhitnitsky

Example: Strangelets



E. Farhi and R. L. Jaffe, Phys. Rev. D 30, 2379 (1984)
E. Witten, Phys. Rev. D 30, 272 (1984)
A. R. Bodmer, Phys. Rev. D 4, 1601 (1971)

- Quark matter: consists of quarks not bound to baryons
- Presence of strange quark can lower the energy of such objects and make them stable
- A stable composite particle which consists of large number of up down and strange quarks – dark matter particle candidate
- Neutron stars could have a quark core with strange quarks (debated)

radiation from antiquark nuggets

- Electron-positron and quark-antiquark annihilations in collisions of visible matter with anti-quark nuggets
- We study the radiation in such collisions and compare it with satellite observations of the center of our galaxy, cold molecular clouds and solar corona. Microwave, infrared, visible, UV, 511 keV, 100-500 MeV
- Shock waves from atmosphere and earth –infrasonic, acoustic and seismic signals

Budker. V.F. and Zhitnitsky; V.F. and I. Samsonov, PRD + arXiv 2020-2022

Possible regular component of Parity violation due to mixing of octupole doublet states

- We link this regular effect to the mixing of close opposite parity rotational doublet states in nuclei which are theorised to have an octupole deformation
- There are indications that ^{233}Th has octupole deformation in the excited state after neutron capture (in nearby isotopes there are doublets in the ground state).
- We suggested other candidate nuclei which may have octupole deformation, and hence a regular effect:

$$^{141}_{59}\mathrm{Pr}_{82},\ ^{143}_{60}\mathrm{Nd}_{83},\ ^{145}_{60}\mathrm{Nd}_{85},\ ^{147}_{62}\mathrm{Sm}_{85},\ ^{151}_{63}\mathrm{Eu}_{88},\ ^{153}_{63}\mathrm{Eu}_{90},\ ^{155}_{64}\mathrm{Gd}_{91},\ ^{157}_{64}\mathrm{Gd}_{93},\ ^{159}_{65}\mathrm{Tb}_{94},\ ^{161}_{66}\mathrm{Dy}_{95},\ ^{163}_{66}\mathrm{Dy}_{97}\ldots$$

- The existence of this mechanism would potentially provide a new way to search for nuclei with octupole deformation.

Anapole and weak quadrupole

Nuclear spin-dependent interactions are dominated by anapole moment (V.F. and Khriplovich 1980)

and weak quadrupole moment (Sushkov and V.F. 1978).

Measurements of weak quadrupole will give us values of the quadrupole moments of neutron distribution (unknown!).

Enhanced in molecules due to close opposite parity rotational doublets.

T-invariance: Weak charge contribution is not enhanced.

We performed nuclear, atomic and molecular calculations. $|J_1-J_2|=1$ anapole, $|J_1-J_2|=2$ quadrupole

Nuclear EDM-screening: d_N E_N

- Oscillating field: incomplete screening!

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

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

$\varsigma = 2eE_0 \langle 0|D_z|n \rangle$ 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.

Summary

Schiff moment is enhanced up to 1000 times in nuclei with octupole deformation → radioactive molecules RaO, AcN, ThO, Np ,… Stable EuN ? Nuclear spin $I \geq \frac{1}{2}$

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

Nuclear spin $I \geq 1$, electron $J \geq 1/2$; *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 $J \geq 1/2$

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

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

Weak quadrupole → nuclear neutron quadrupole