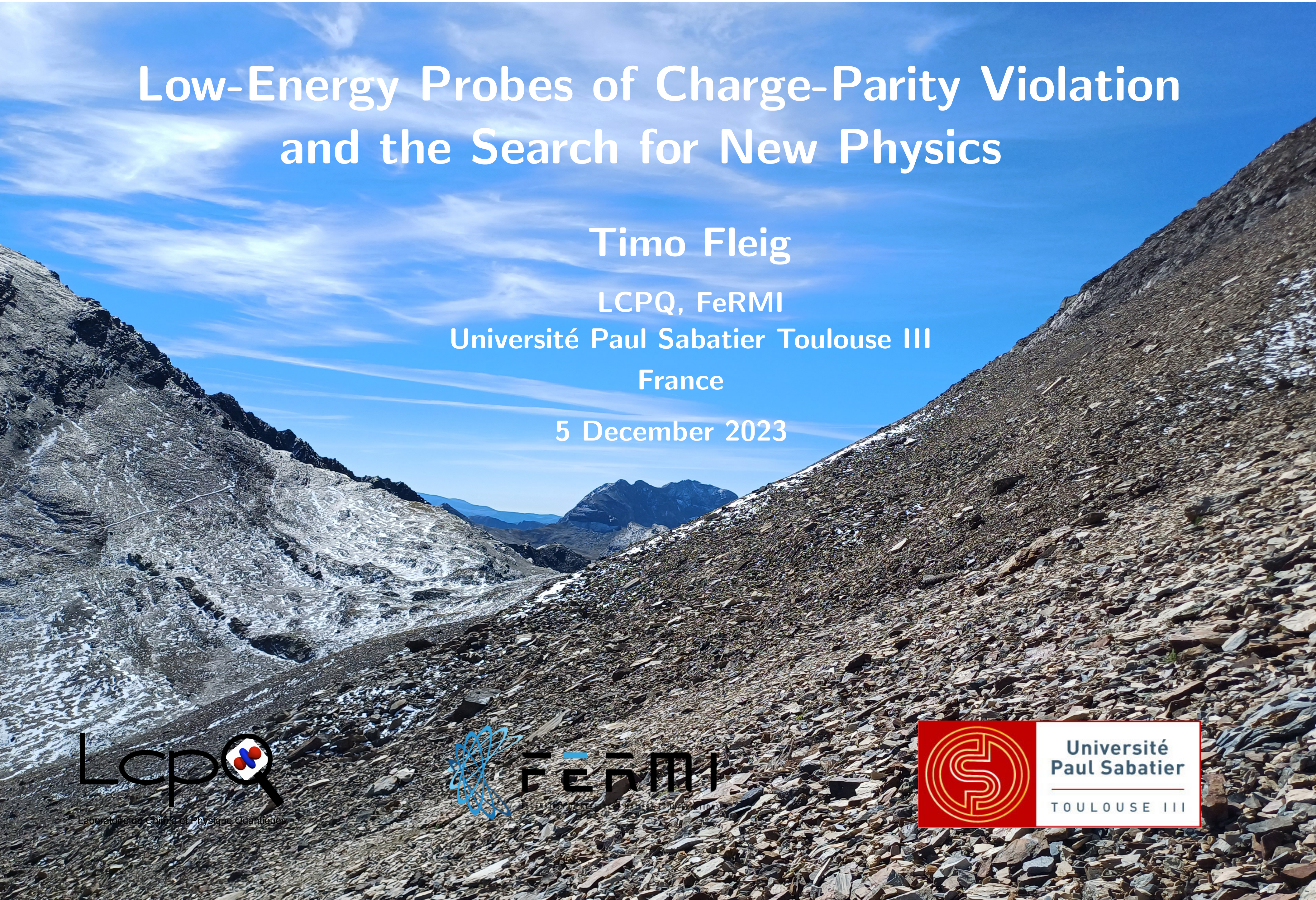


Low-Energy Probes of Charge-Parity Violation and the Search for New Physics

Timo Fleig

LCPQ, FeRMI
Université Paul Sabatier Toulouse III
France

5 December 2023

Outline

The search for New Physics in EDMs: **The big picture**

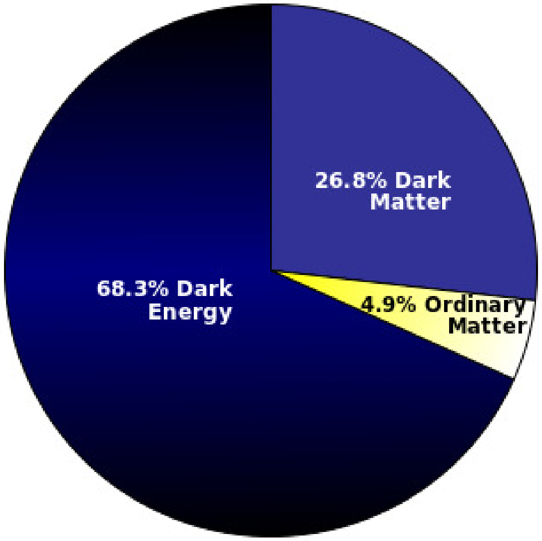
From particle physics to a fermion EDM

atomic physics of EDMs

Search for a lepton EDM: **Electron EDM** in RaAg

Hadron-sector searches: Tensor-pseudotensor interaction in TlF

Energy Content and Baryon Asymmetry of the Universe (BAU)[1]



Dark energy: Why accelerated expansion? Cosmological constant?

Dark matter: Particle (LSP, axion)? Modification of gravity?

Ordinary matter: Existence contradicts SM prediction!

Evidence for the BAU:

$$Y_B = \frac{n_B - \overline{n}_B}{S} \approx \frac{n_B}{S} = \begin{cases} (7.3 \pm 2.5) \times 10^{-11} & \text{Big-Bang Nucleosynthesis (BBN)}^2 \\ (9.2 \pm 1.1) \times 10^{-11} & \text{(WMAP, exp.)}^3 \\ (8.59 \pm 0.11) \times 10^{-11} & \text{(Planck, exp.)}^4 \end{cases}$$

---

[1] G. A. White, *A Pedagogical Introduction to Electroweak Baryogenesis* **Morgan & Clay** (2016) *1*

[2] S. Eidelman *et al.*, *Rev. Part. Phys. Phys. Lett. B* **592** (2004) *1*

[3] D. N. Spergel *et al.*, *Astron. J. Suppl.* **148** (2003) *175*

[4] P. A. R. Ade *et al.*, *Astron. Astrophys.* **571** (2013) *A16*

Explaining the Matter Content of the Universe?

Antimatter is not hidden in a pocket.[5]

($\mathcal{CP}$)-Violation **required** to explain BAU.[6] ("Sakharov conditions")

Matter-antimatter dissymmetry known from heavy meson decays[7]

$$K_L \longrightarrow \begin{cases} \pi^+ + e^- + \overline{\nu}_e & (-) \\ \pi^- + e^+ + \nu_e & (+) \end{cases}$$

$\delta = \frac{N^+ - N^-}{N^+ + N^-} \approx 3 \times 10^{-3}$

Built into SM through CKM formalism.[8]

However, not enough to explain BAU. (**Leptogenesis**[9], **Electroweak baryogenesis**[10]

---

[5] A.G. Cohen, A. De Rújula, S.L. Glashow, *Astrophys J* **495** (1998) *539*

[6] A. D. Sakharov, *JETP Lett.* **5** (1967) *24*

[7] S. Gjesdal et al., *Phys Lett* **52B** (1974) *113*
F. Wilczek (1980)

[8] C. Cabibbo, *Phys Rev Lett* **10** (1963) *531*
M. Kobayashi, K. Maskawa, *Prog Theor Phys* **49** (1973) *652*

[9] S. Davidson, E. Nardi, Y. Nir, *Phys Rep* **466** (2008) *105*

[10] D.E. Morrissey, M.J. Ramsey-Musolf, *New J Phys* **14** (2012) *125003*

$(\mathcal{C}\mathcal{P})$-Violation and the $(\mathcal{C}\mathcal{P}\mathcal{T})$ Theorem[11]

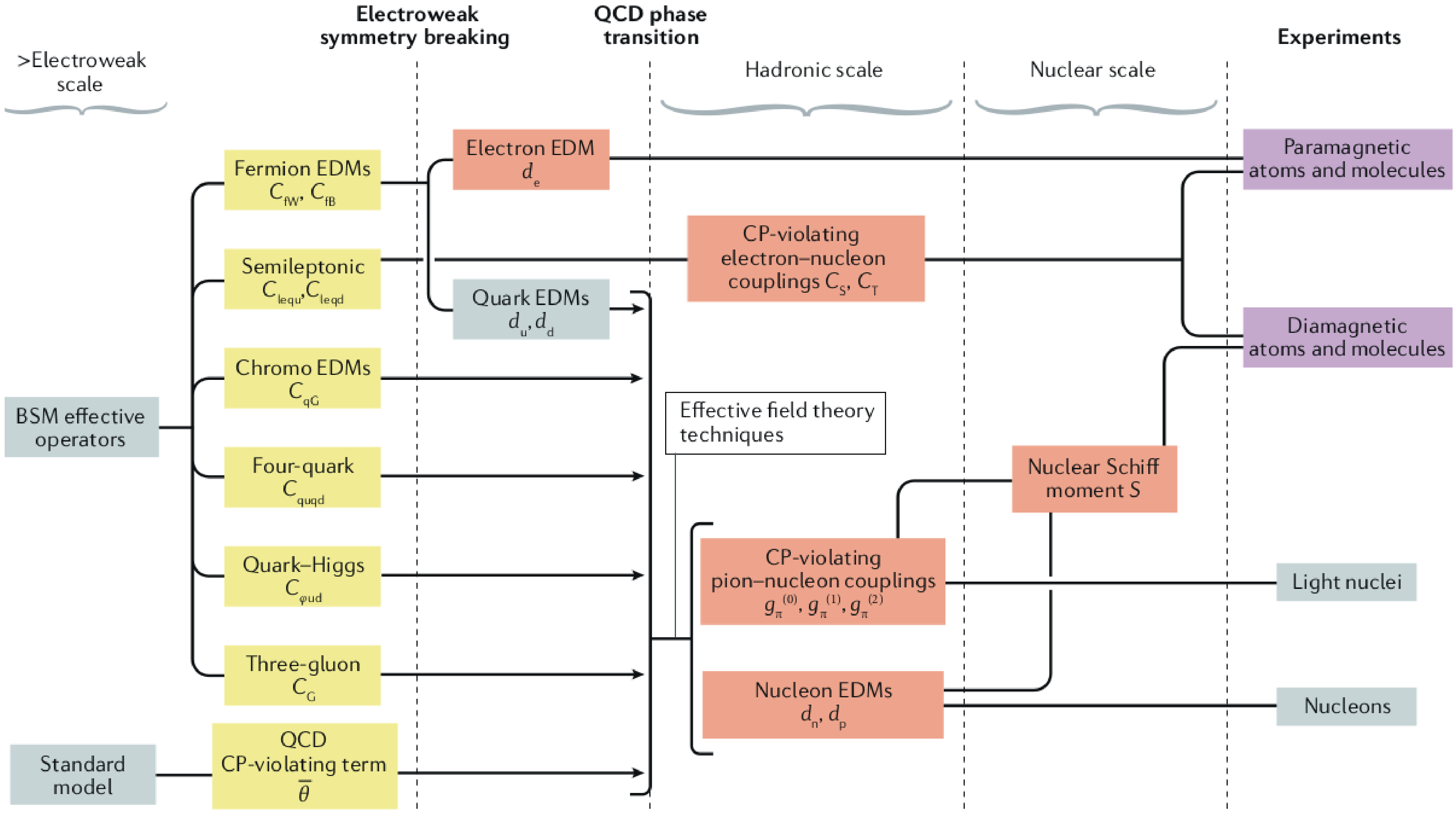
$$(\cancel{\mathbf{CP}}) \xrightarrow{\mathbf{CPT}} (\cancel{\mathbf{T}})$$

EDMs violate $\mathcal{T}$ symmetry

---

[11] W. Pauli, *Niels Bohr and the Development of Physics* (1955) *30*

EDMs and their possible sources: An overview



>Electroweak scale

Electroweak symmetry breaking

QCD phase transition

Hadronic scale

Nuclear scale

Experiments

BSM effective operators

Fermion EDMs C_{fW}, C_{fB}

Semileptonic C_{lequ},C_{leqd}

Chromo EDMs C_{qG}

Four-quark C_{quqd}

Quark–Higgs $C_{\varphi ud}$

Three-gluon C_G

Standard model

QCD CP-violating term $\bar{\theta}$

Electron EDM d_e

Quark EDMs d_u, d_d

CP-violating electron–nucleon couplings C_S, C_T

Effective field theory techniques

CP-violating pion–nucleon couplings $g_\pi^{(0)}$, $g_\pi^{(1)}$, $g_\pi^{(2)}$

Nucleon EDMs d_n, d_p

Nuclear Schiff moment S

Paramagnetic atoms and molecules

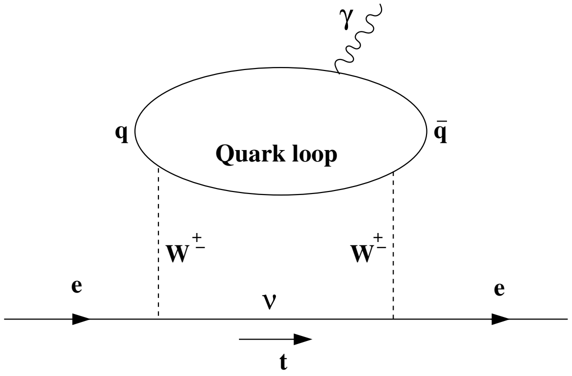
Diamagnetic atoms and molecules

Light nuclei

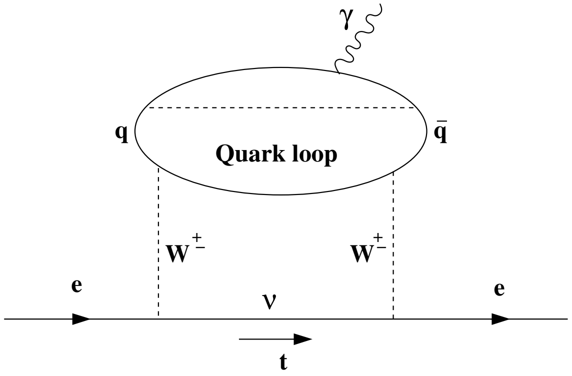
Nucleons

W. Cairncross, J. Ye, *Nat. Rev. Phys.* **1** (2019) *510*

Standard-Model Prediction of the Electron EDM

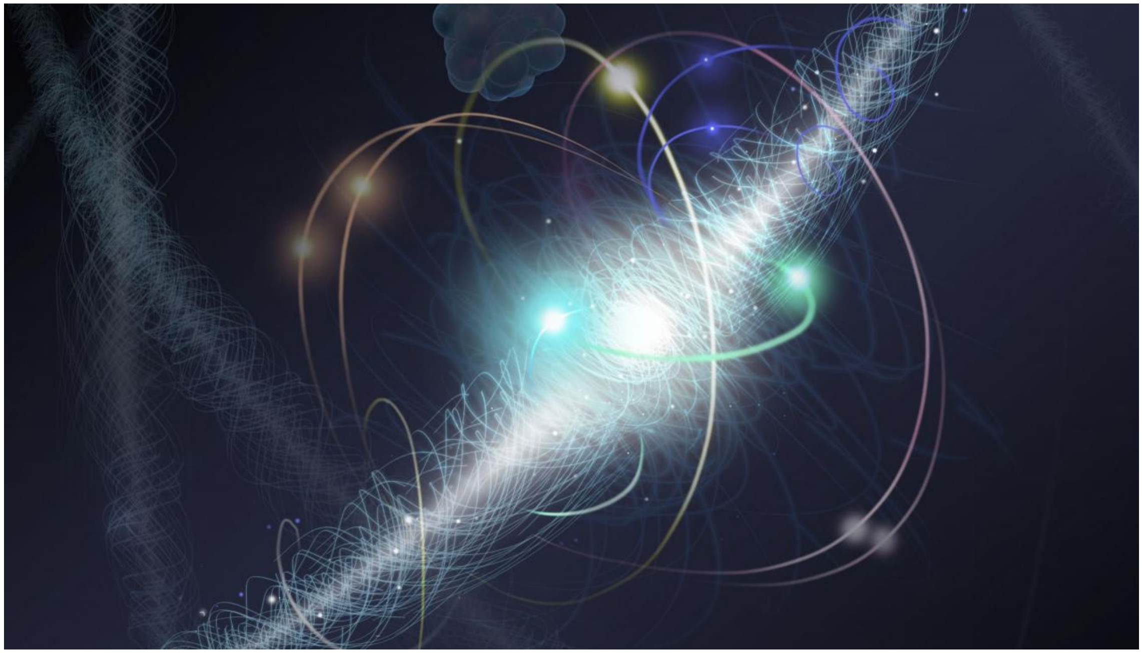


Summed two-loop diagrams[12]
$\Rightarrow d_e = 0$



Summed three-loop diagrams[12]
$\Rightarrow d_e = 0$

Interactions with virtual particles including $\mathcal{CP}$-violation
$\Rightarrow$ fermion EDM


[13]

The SM eEDM is extremely small: $d_e \approx 10^{-35}\,e$cm

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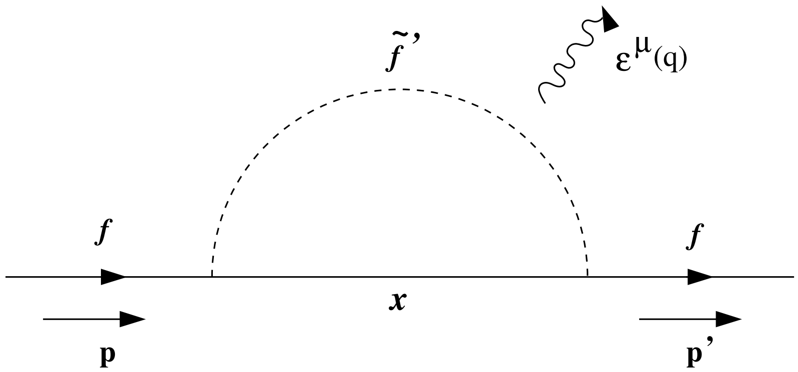
[12] M.É. Pospelov, I.B. Khriplovich, *Yad. Fiz.* **53** (1991) *1030*
Y. Ema, T. Gao, M.É. Pospelov, *Phys. Rev. Lett.* **129** (2022) *231801*

[13] https://www.pourlascience.fr/sd/physique-particules/lelectron-met-a-mal-des-theories-au-dela-du-modele-standard-15089.php

Beyond the Standard Model Predictions of eEDM



χ: chargino, neutralino

$\tilde{f}'_j$: supersymmetry (s)-fermion

$\epsilon^{\mu}(q)$: photon

Chargino ($\tilde{\chi}^{\pm}_{1,2}$), neutralino ($\tilde{\chi}^{0}_{1,2,3,4}$) or gluino ($\tilde{g}^{a}$) fermion/sfermion interaction Lagrangian:

$$\mathcal{L}_{\chi f \tilde{f}'} = g^{\chi f \tilde{f}'_j}_{Lij} \left(\overline{\chi}_i P_L f\right) \tilde{f}'^{*}_j + g^{\chi f \tilde{f}'_j}_{Rij} \left(\overline{\chi}_i P_R f\right) \tilde{f}'^{*}_j + h.c.$$

One-loop fermion EDM:[14]

$$\left(\frac{d^E_f}{e}\right)^{\chi} = \frac{m_{\chi_i}}{16\pi^2 m^2_{\tilde{f}'_j}} \mathcal{I}m\left[\left(g^{\chi f \tilde{f}'_j}_{Rij}\right)^{*} g^{\chi f \tilde{f}'_j}_{Lij}\right] \left[Q_{\chi} A\left(\frac{m_{\chi_i}}{m^2_{\tilde{f}'_j}}\right) + Q_{\tilde{f}'_j} B\left(\frac{m_{\chi_i}}{m^2_{\tilde{f}'_j}}\right)\right]$$

MSSM prediction:

$d_e \leq 10^{-27}\, e$ cm

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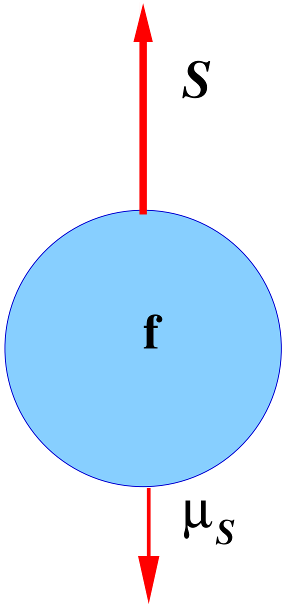
[14] J. Ellis, J.S. Lee, A. Pilaftsis, *J High Energy Phys* **10** (2008) *049*

The Fermion Magnetic Dipole Moment (fMDM)



$$\boldsymbol{\mu}_f = g_f \, \frac{q_f}{2m_f c} \, \boldsymbol{S} = \gamma_f \, \boldsymbol{S}$$

The “Jewel” of physics ($f \to e$):

Experiment: $g_e/2 = 1.001\,159\,652\,180\,59\,(13)$[15]

Theory: $g_e/2 = 1.001\,159\,652\,180\,(0.7)$[16]

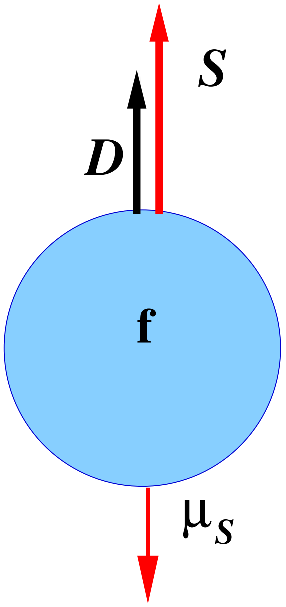
---

[15] X. Fan and T. G. Myers and A. D. Sukra and G. Gabrielse, *Phys. Rev. Lett.* **130** (2023) *071801*

[16] T. Aoyama, T. Kinoshita, M. Nio, *Phys. Rev. D* **97** (2018) *036001*
Jegerlehner Fred, EPJ Web Conf. 218, 01003 (2019)., *EPJ Web Conf.* **218** (2019) *01003*
A. Czarnecki, W. J. Marciano, and A. Vainshtein, *Phys. Rev. D* **67** (2003) *073006*

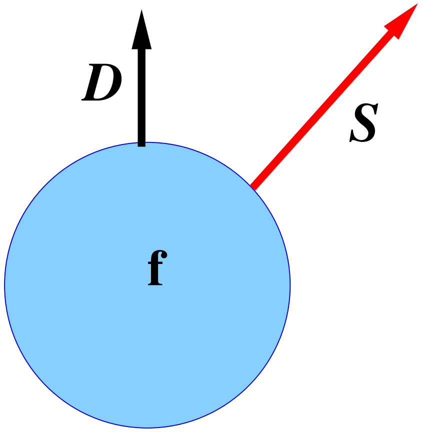
The Fermion Electric Dipole Moment (fEDM)

Why



?

and not



?

Sets of valid quantum numbers for fermion state:

$|C, T, U, \ldots, s, m_s\rangle$

$|C, T, U, \ldots, s, m_s, m_{\mathsf{EDM}}\rangle$

On the rhs. the many-fermion state could be written:

$$|C(1) = C(2), T(1) = T(2), \ldots, s(1) = s(2), m_s(1) = m_s(2), m_{\mathsf{EDM}}(1) \neq m_{\mathsf{EDM}}(2)\rangle$$

which contradicts observation !

The Fermion EDM

Hamiltonian in Electromagnetic Field

Classical electromagnetism:

$\varepsilon_{\mathrm{dip}} = -\mathbf{D} \cdot \mathbf{E}$

Fermion EDM vector operator $\hat{\mathbf{d}} \propto \mathbf{\Sigma} = \begin{pmatrix} \boldsymbol{\sigma} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{\sigma} \end{pmatrix}$ and so[17]

$\hat{H}_{\textsf{EDM}} = -d_f \, \gamma^0 \, \mathbf{\Sigma} \cdot \mathbf{E}$

The proportionality constant d_f is the fermion EDM.

Dirac matrix γ^0 ensures that $\left\langle \hat{H} \right\rangle$ is a Lorentz scalar

Energy $\left\langle \hat{H} \right\rangle$ *violates* space-inversion ($\mathcal{P}$) and time-reversal ($\mathcal{T}$) symmetries:

$\left(\gamma^0\right)^{-1} \; \gamma^0 \, \mathbf{\Sigma} \; \gamma^0 = \gamma^0 \, \mathbf{\Sigma}$ $\qquad$ $\mathcal{P}^{-1} \; \mathbf{E} \; \mathcal{P} =$ -$\mathbf{E}$

$\left(\imath\gamma^0\gamma^5\gamma^2 \, \hat{K}_0\right)^{-1} \; \gamma^0 \, \mathbf{\Sigma} \; \imath\gamma^0\gamma^5\gamma^2 \, \hat{K}_0 = -\gamma^0 \, \mathbf{\Sigma}$ $\qquad$ $\mathcal{T}^{-1} \; \mathbf{E} \; \mathcal{T} = \mathbf{E}$

This energy $\left\langle \hat{H} \right\rangle$ is a $\mathcal{T}$-odd *pseudo*scalar.

---

[17] E. Salpeter, *Phys Rev* **112** (1958) *1642*

Atomic EDM

Schiff's Theorem

"The electric dipole moment of a bound-state atom composed of particles with non-zero electric dipole moments is zero in non-relativistic approximation."[18]

Consider the expectation value in eigenstate $\psi^{(0)}$ (incl. E_{ext})

$$\varepsilon_{\text{EDM}} = \left\langle -d_e \gamma^0 \mathbf{\Sigma} \cdot \mathbf{E} \right\rangle_{\psi^{(0)}} = \left\langle -d_e \mathbf{\Sigma} \cdot \mathbf{E} \right\rangle_{\psi^{(0)}} + \left\langle d_e (\mathbb{1}_4 - \gamma^0) \mathbf{\Sigma} \cdot \mathbf{E} \right\rangle_{\psi^{(0)}}$$

In the non-rel. limit $\gamma^0 \overset{\text{nrlimit}}{\longrightarrow} \mathbb{1}_4$ and so we consider

$$\begin{aligned} \left\langle -d_e \mathbf{\Sigma} \cdot \mathbf{E} \right\rangle_{\psi^{(0)}} &= \frac{-d_e}{-e} \left\langle \mathbf{\Sigma} \cdot (\nabla_{\mathbf{x}}\, e\phi) \right\rangle_{\psi^{(0)}} = \frac{\imath d_e}{e\hbar} \left\langle [\mathbf{\Sigma} \cdot \mathbf{p}, e\phi \mathbb{1}_4] \right\rangle_{\psi^{(0)}} \\ &= \frac{\imath d_e}{e\hbar} \left\langle \left[\mathbf{\Sigma} \cdot \mathbf{p}, c\boldsymbol{\alpha} \cdot \mathbf{p} + \gamma^0 m_0 c^2 - \hat{H}^{(0)} \right] \right\rangle_{\psi^{(0)}} \end{aligned}$$

Since $\hat{H}^{(0)} \left|\psi^{(0)}\right\rangle = E^{(0)} \left|\psi^{(0)}\right\rangle$ all commutators vanish, and so

$$\left\langle -d_e \mathbf{\Sigma} \cdot \mathbf{E} \right\rangle_{\psi^{(0)}} = 0 \quad \square.$$

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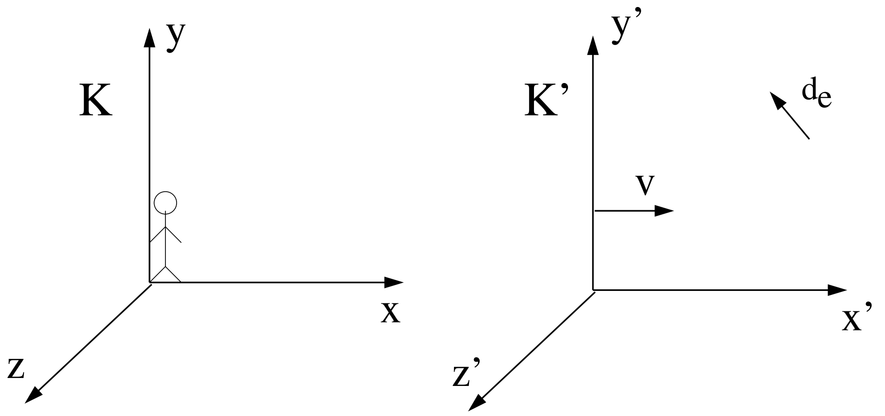
[18] L.I. Schiff, *Phys Rev* **132** (1963) *2194*

Atomic EDM

Evading Schiff's Theorem by Special Relativity[19]



Length contraction for collinear movement:

$$\mathbf{d}_e(K) = \frac{\mathbf{d}_e(K')}{\gamma} = \mathbf{d}_e(K')\left(1 - \frac{\gamma}{1+\gamma}\frac{v^2}{c^2}\right)$$

... and for general movement:

$$\mathbf{d}_e(K) = \mathbf{d}_e(K') - \frac{\gamma}{1+\gamma}\frac{\mathbf{v}}{c}\left(\mathbf{d}_e(K')\cdot\frac{\mathbf{v}}{c}\right)$$

The dipole energy in K then is

$$\varepsilon_{\mathsf{dip}} = -\mathbf{d}_e(K)\cdot\mathbf{E} = -\mathbf{d}_e(K')\cdot\left[\mathbf{E} - \frac{\gamma}{1+\gamma}\frac{\mathbf{v}}{c}\left(\frac{\mathbf{v}}{c}\cdot\mathbf{E}\right)\right]$$

For small relative velocities we can approximate:

$$\varepsilon_{\mathsf{dip}} \approx -\mathbf{d}_e(K')\cdot\mathbf{E} + \frac{1}{2m_e^2c^2}\mathbf{d}_e(K')\cdot\mathbf{p}\,(\mathbf{p}\cdot\mathbf{E})$$

---

[19] E.D. Commins, J.D. Jackson, D.P. DeMille, *Am J Phys* **75** (2007) *532*

Atomic EDM

Interpretation of the EDM Interaction

The $\mathcal{P},\mathcal{T}$-odd energy can also be written as

$$\varepsilon_{\mathsf{EDM}} = -d_e \left\langle \Psi^L \; \Psi^S \left| \begin{pmatrix} \mathbf{1}_2 & \mathbf{0}_2 \\ \mathbf{0}_2 & -\mathbf{1}_2 \end{pmatrix} \begin{pmatrix} \boldsymbol{\sigma}\cdot\mathbf{E} & \mathbf{0}_2 \\ \mathbf{0}_2 & \boldsymbol{\sigma}\cdot\mathbf{E} \end{pmatrix} \right| \begin{matrix} \Psi^L \\ \Psi^S \end{matrix} \right\rangle$$

$$= -d_e \left\{ \left\langle \Psi^L \left| \boldsymbol{\sigma}\cdot\mathbf{E} \right| \Psi^L \right\rangle - \left\langle \Psi^S \left| \boldsymbol{\sigma}\cdot\mathbf{E} \right| \Psi^S \right\rangle \right\}$$

Using the low-energy relationship between L and S components of the Dirac spinors $\Psi^S \approx \frac{\boldsymbol{\sigma}\cdot\hat{\mathbf{p}}}{2mc}\Psi^L$ gives

$$\approx -d_e \left\{ \langle \boldsymbol{\sigma}\cdot\mathbf{E} \rangle_{\Psi^L} - \frac{1}{4m^2c^2} \left\langle (\boldsymbol{\sigma}\cdot\hat{\mathbf{p}})^\dagger \, \boldsymbol{\sigma}\cdot\mathbf{E} \, \boldsymbol{\sigma}\cdot\hat{\mathbf{p}} \right\rangle_{\Psi^L} \right\}$$

Respecting the derivative and using twice the Dirac relation

$$\boldsymbol{\sigma}\cdot\hat{\mathbf{p}} \; \boldsymbol{\sigma}\cdot\mathbf{E} = \hat{\mathbf{p}}\cdot\mathbf{E}\mathbf{1}_2 + \imath\boldsymbol{\sigma}\cdot\hat{\mathbf{p}}\times\mathbf{E}$$

we finally get

$$\varepsilon_{\mathsf{EDM}} \approx -d_e \left\{ \langle \boldsymbol{\sigma}\cdot\mathbf{E} \rangle_{\Psi^L} - \frac{1}{4m^2c^2} \left[\langle \hat{\mathbf{p}}\cdot\mathbf{E} \, \boldsymbol{\sigma}\cdot\hat{\mathbf{p}} \rangle_{\Psi^L} + \langle \mathbf{E}\cdot\hat{\mathbf{p}} \, \boldsymbol{\sigma}\cdot\hat{\mathbf{p}} \rangle_{\Psi^L} \right] \right\}$$

which corresponds to the classical dipole energy in the observer frame.

Atomic EDM

Lorentz-Covariant eEDM Hamiltonian

Fields $(\mathbf{E}, \mathbf{B})$ in the lab frame transform into fields $(\mathbf{E}', \mathbf{B}')$ in some other Lorentz frame.

Covariant single-particle eEDM Hamiltonian:

$$\hat{H}_{\mathrm{EDM}} = \imath \frac{d_e}{2} \gamma^0 \gamma^5 \frac{\imath}{2} \left(\gamma^\mu \gamma^\nu - \gamma^\nu \gamma^\mu\right) F_{\mu\nu}$$

Use covariant EM field tensor

$$\{F_{\mu\nu}\} = \{\partial_\mu A_\nu - \partial_\nu A_\mu\} = \begin{pmatrix} 0 & E_x & E_y & E_z \\ -E_x & 0 & -B_z & B_y \\ -E_y & B_z & 0 & -B_x \\ -E_z & -B_y & B_x & 0 \end{pmatrix}$$

to derive conventional representation of form-invariant Hamiltonian:

$$\hat{H}_{\mathrm{EDM}} = -d_e \gamma^0 \left[\mathbf{\Sigma} \cdot \mathbf{E} + \imath \boldsymbol{\alpha} \cdot \mathbf{B}\right]$$

Off-diagonal $\boldsymbol{\alpha} = \begin{pmatrix} \mathbf{0}_2 & \boldsymbol{\sigma} \\ \boldsymbol{\sigma} & \mathbf{0}_2 \end{pmatrix}$ couples Ψ^L and Ψ^S and suppresses $\mathbf{B}$ term

One-body Hamiltonian in n-body system:

$$\hat{H}_{\mathrm{EDM}} = -d_e \sum_j^n \gamma^0(j) \left[\mathbf{\Sigma}(j) \cdot \mathbf{E}(\mathbf{r}_j) + \imath \boldsymbol{\alpha}(j) \cdot \mathbf{B}(\mathbf{r}_j)\right]$$

Atomic EDM

Definition and eEDM enhancement

Electric dipole moment of an atom:[20]

$d_a := -\lim_{E_{\text{ext}}\to 0}\left[\frac{\partial(\Delta\varepsilon_{\not{P}\not{T}})}{\partial E_{\text{ext}}}\right]$ $\Delta\varepsilon_{\not{P}\not{T}}$ is **some** P, T-odd energy shift.

Sources are particle EDMs, nuclear MQM, nuclear Schiff moment, $\mathcal{T}$-odd contribution to weak interaction.

For an electron EDM, we then have

$$d_a = \lim_{E_{\text{ext}}\to 0}\frac{\partial}{\partial E_{\text{ext}}} d_e \left\langle \gamma^0 \left[\boldsymbol{\Sigma}\cdot\mathbf{E} + \imath\boldsymbol{\alpha}\cdot\mathbf{B}\right]\right\rangle_{\psi(E_{\text{ext}})}$$

With the definitions $(E+B)_{\text{eff}} = -\left\langle \gamma^0 \left[\boldsymbol{\Sigma}\cdot\mathbf{E} + \imath\boldsymbol{\alpha}\cdot\mathbf{B}\right]\right\rangle_{\psi(E_{\text{ext}})}$

$R := \frac{d_a}{d_e}$ $R_{\text{lin}} := -\frac{\Delta(E+B)_{\text{eff}}}{\Delta E_{\text{ext}}} = -\frac{(E+B)_{\text{eff}}(2) - (E+B)_{\text{eff}}(1)}{E_{\text{ext}}(2) - E_{\text{ext}}(1)}$

the linear-regime atomic eEDM enhancement is then:

$$R \approx R_{\text{lin}} = -\frac{(E+B)_{\text{eff}}}{E_{\text{ext}}}$$

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[20] E.D. Commins, *Adv. Mol. Opt. Phys.* **40** (1999) *1*

Atomic EDM

Scaling and Choice of Sensitive Systems

An **atom** can be much **more sensitive** than a free electron! (Sandars effect)[21]

Analytical estimates of the eEDM enhancement[22]

$R \propto 10\, Z^3 \alpha^2$

High-Z atoms with unpaired electron shells are optimal choice:

Atom (state)	Rb ($^2S_{1/2}$)	Cs ($^2S_{1/2}$)	Fr ($^2S_{1/2}$)	Tl ($^2P_{1/2}$)
Z	37	55	87	81
R	26 ± 1[23]	114 ± 3[24]	910 ± 45[25]	-559 ∓ 28[26]

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[21] P.G.H. Sandars, *Phys Lett* **14** (1965) *194*

[22] E.D. Commins, D. DeMille, *Adv. Ser. Dir. High En. Phys.* **chapter 14** (2008) *519*
V.V. Flambaum, *Sov. J. Nucl. Phys.* **24** (1976) 199

[23] A. Shukla, B.P. Das, J. Andriessen, *Phys. Rev. A* **50** (1994) 1155

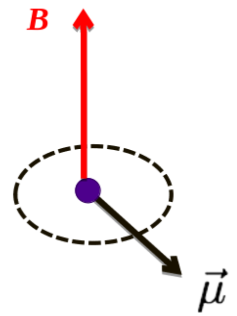
[24] A. C. Hartley, E. Lindroth, A.-M. Mårtensson-Pendrill, *J. Phys. B: At. Mol. Opt. Phys.* **23** (1990) 3417

[25] T.M.R. Byrnes, V.A. Dzuba, V.V. Flambaum, D.W. Murray, *Phys. Rev. A* **59** (1999) 3082

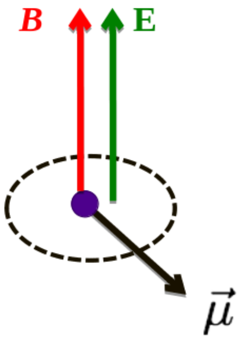
[26] T. F., L.V. Skripnikov, *Symmetry* **12** (2020) 498

Atomic-Scale EDM

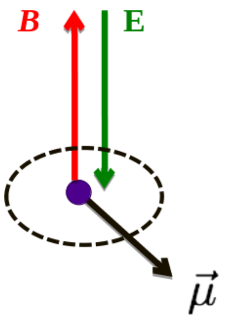
Measurement Principle of $\Delta\varepsilon_{\not{P}\not{T}}$[27]



(1)



(2)



(3)

Hamiltonian of sensitive system in external EM field:

$$\hat{H} = -(\mu\mathbf{B} + d\mathbf{E}) \cdot \frac{\hat{\mathbf{J}}}{|J|}$$

(1) B-field causes spin precession with frequency ν:

$$-(\mu\mathbf{B}) \cdot \frac{\hat{\mathbf{J}}}{|J|} = h\nu$$

(2) Added E-field modifies spin precession freq. to ν_+:

$$-(\mu\mathbf{B} + d\mathbf{E}) \cdot \frac{\hat{\mathbf{J}}}{|J|} = h\nu_+$$

(3) Reversed E-field modifies spin precession freq. to ν_-:

$$-(\mu\mathbf{B} - d\mathbf{E}) \cdot \frac{\hat{\mathbf{J}}}{|J|} = h\nu_-$$

EDM of system can be extracted from:

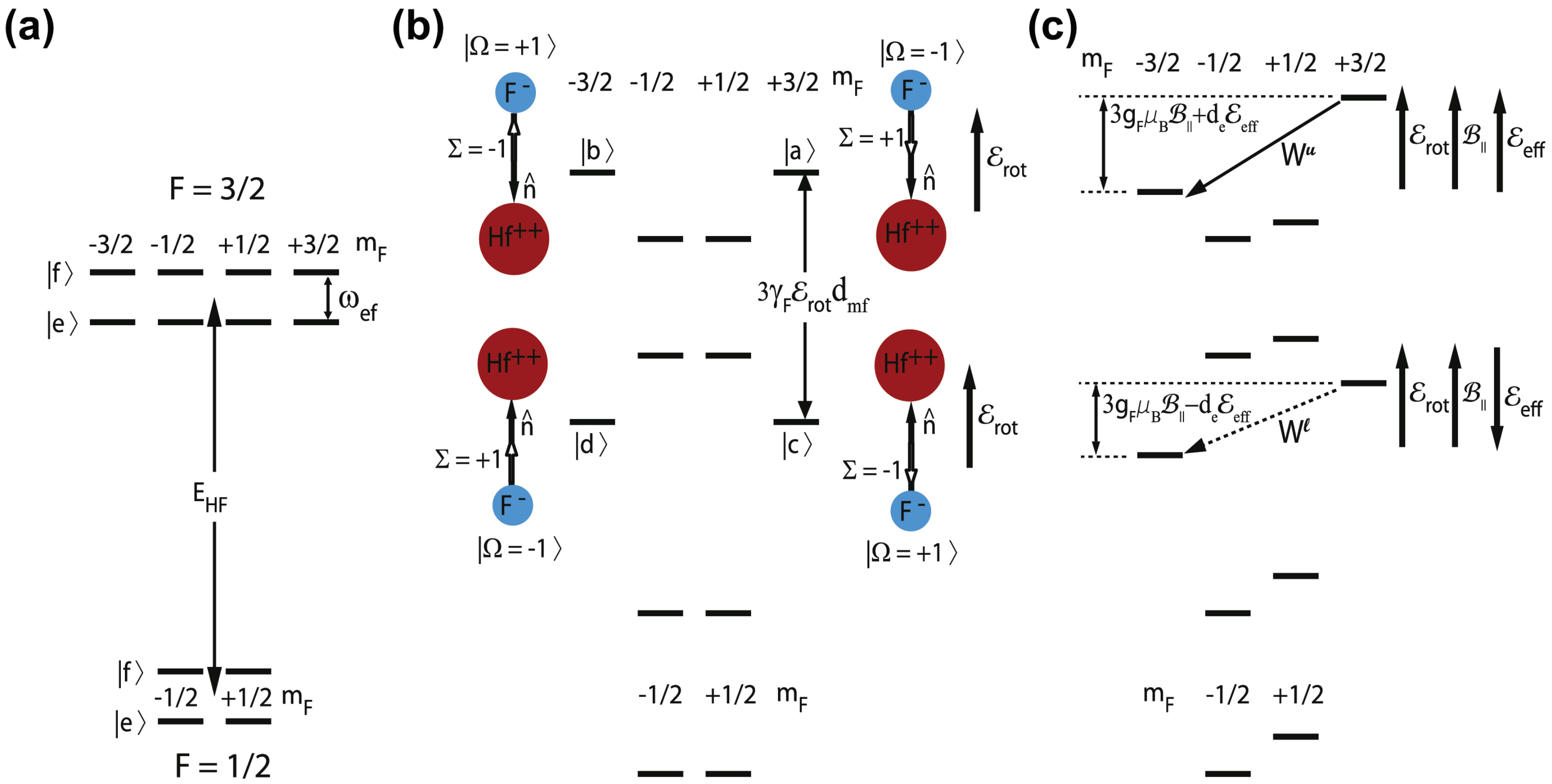
$$\nu_+ - \nu_- = \frac{2dE|J|}{h} \quad \Leftrightarrow \quad d = \frac{h(\nu_+ - \nu_-)}{2E|J|}$$

---

[27] M. Bishof, M. Dietrich, *et al.*, *Phys. Rev. C* **94** (2016) 025501
B. C. Regan, E. D. Commins, C. J. Schmidt, D. DeMille, *Phys. Rev. Lett.* **88** (2002) 071805

EDM Measurement in Molecules

HfF$^+$ as Example[28]



$$\frac{W^u(B)+W^u(-B)}{2E_{\mathrm{eff}}} = d_e$$

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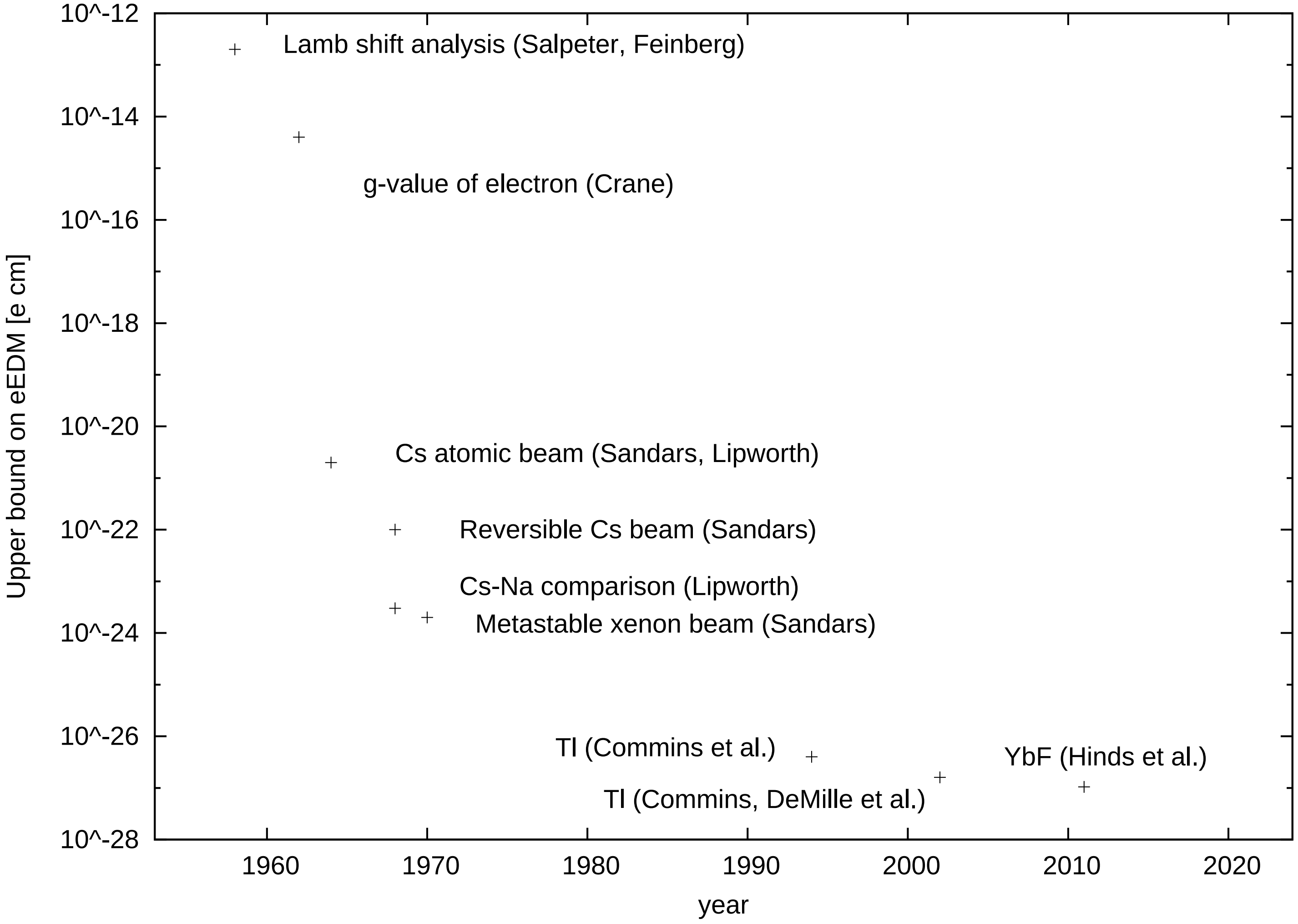
[28] A.E. Leanhardt *et al.*, E.A. Cornell, *J Mol Spectrosc* **270** (2011) *1*
W.B. Cairncross *et al.*, J. Ye, E.A. Cornell, *Phys Rev Lett* **119** (2017) *153001*

Electron Electric Dipole Moment

Historic Upper Bounds From Atomic EDM Measurements



Atomic and Molecular Correlated Wavefunctions[29]

Hamiltonians

- Dirac-Coulomb Hamiltonian + external electric field (atoms)

$$\hat{H}^{\text{Dirac-Coulomb}} + \hat{H}^{\text{Int-Dipole}} = \sum_{i}^{n} \left[c\,\boldsymbol{\alpha}_i \cdot \mathbf{p}_i + \beta_i c^2 - \frac{Z}{r_i}\mathbb{1}_4 \right] + \sum_{i,j>j}^{n} \frac{1}{r_{ij}}\mathbb{1}_4 + \sum_{i}^{n} \mathbf{r}_i \cdot \mathbf{E}_{\text{ext}}\,\mathbb{1}_4$$

- Dirac-Coulomb Hamiltonian operator (molecules)

$$\hat{H}^{DC} = \sum_{i}^{n} \left[c\,\boldsymbol{\alpha}_i \cdot \mathbf{p}_i + \beta_i c^2 - \sum_{A}^{N} \frac{Z}{r_{iA}}\mathbb{1}_4 \right] + \sum_{i,j>i}^{n} \frac{1}{r_{ij}}\mathbb{1}_4 + \sum_{A,B>A}^{N} V_{AB}$$

- Dirac-Coulomb-Gaunt Hamiltonian operator (molecules)

$$\hat{H}^{DCG} = \sum_{i}^{n} \left[c\,\boldsymbol{\alpha}_i \cdot \mathbf{p}_i + \beta_i c^2 - \sum_{A}^{N} \frac{Z}{r_{iA}}\mathbb{1}_4 \right] + \sum_{i,j>i}^{n} \left(\frac{1}{r_{ij}}\mathbb{1}_4 - \frac{1}{2}\frac{\vec{\alpha}_i\vec{\alpha}_j}{r_{ij}} \right) + \sum_{A,B>A}^{N} V_{AB}$$

---

[29] T. F., H.J.Å. Jensen, J. Olsen, L. Visscher, *J Chem Phys* **124** (2006) *104106*
S. Knecht, H.J.Å. Jensen, T. F., *J Chem Phys* **132** (2010) *014108*

Calculation of $\mathcal{P},\mathcal{T}$-Violating Effects[30]

String-Based CI Techniques

Expectation values over relativistic Configuration Interaction wavefunctions

$$\left\langle \hat{O} \right\rangle_{\psi_k^{(0)}} = \sum_{I,J=1}^{\mathrm{dim}\mathcal{F}^{\mathrm{t}}(\mathrm{M,n})} c^*_{kI} c_{kJ} \, \langle \, | (\mathcal{S}\overline{\mathcal{T}})^\dagger_I \left| \hat{O} \right| (\mathcal{S}\overline{\mathcal{T}})_J \, | \, \rangle$$

Property operator $\hat{O}$ in basis of Kramers-paired molecular spinors

$$\hat{O} = \sum_{m,n=1}^{P_u} o_{mn}\, a^\dagger_m a_n + \sum_{m=1}^{P_u} \sum_{n=P_u+1}^{P} o_{m\overline{n}}\, a^\dagger_m a_{\overline{n}} + \sum_{m=P_u+1}^{P} \sum_{n=1}^{P_u} o_{\overline{m}n}\, a^\dagger_{\overline{m}} a_n + \sum_{m,n=P_u+1}^{P} o_{\overline{m}\overline{n}}\, a^\dagger_{\overline{m}} a_{\overline{n}}$$

First-term contribution to expectation value

$$W'(\Psi_k)_1 = \sum_{I,J=1}^{\mathrm{dim}\mathcal{F}^{\mathrm{t}}(\mathrm{P,N})} c^*_{kI} c_{kJ} \sum_{m,n=1}^{P_u} o^M_{mn}$$

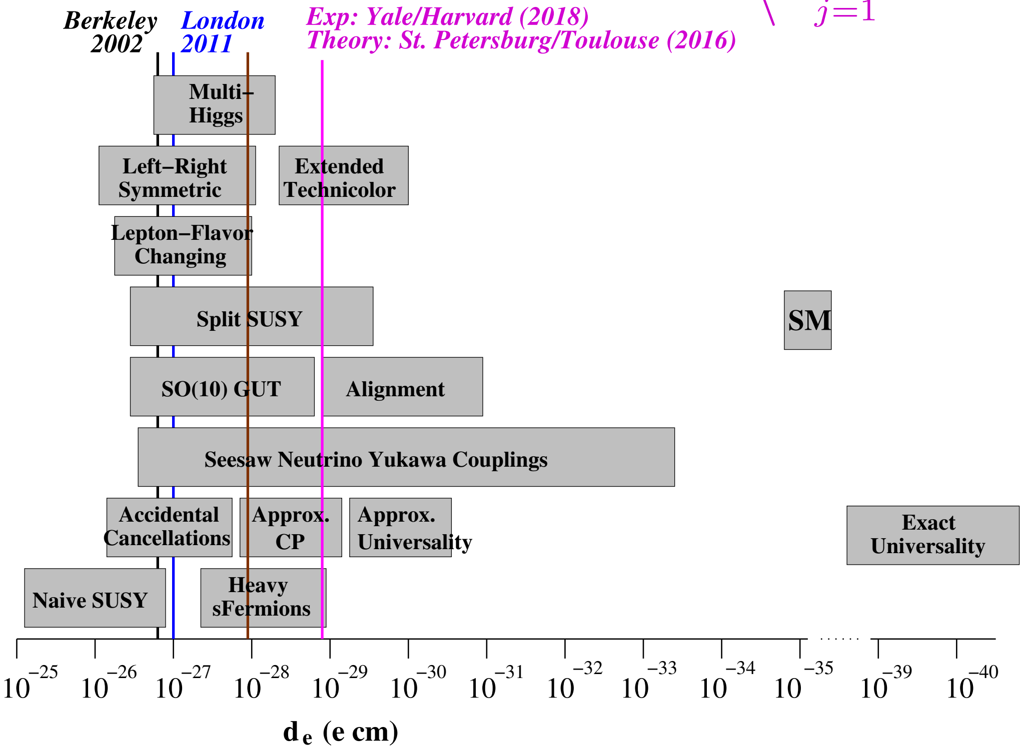
$$\langle \, | \prod_{p=1}^{N_p \in \mathcal{S}_I} \prod_{\overline{p}=N_p+1}^{N_p \in \mathcal{S}_I + N_{\overline{p}} \in \overline{\mathcal{T}}_I} a_{\overline{p}} a_p \, a^\dagger_m a_n \prod_{q=1}^{N_p \in \mathcal{S}_J} \prod_{\overline{q}=N_p+1}^{N_p \in \mathcal{S}_J + N_{\overline{p}} \in \overline{\mathcal{T}}_J} a^\dagger_q a^\dagger_{\overline{q}} \, | \, \rangle$$

---

[30] S. Knecht, Dissertation, HHU Düsseldorf (2009)
T. F., M.K. Nayak, *Phys Rev A* **88** (2013) *032514*

Single-source eEDM Constraint on BSM Theories[31]

$$E_{\text{eff}} = \left\langle -\sum_{j=1}^{n} \gamma^0(j)\,\mathbf{\Sigma}(j)\cdot\mathbf{E}(j)\right\rangle_{\psi(0)} \approx \frac{2\imath c}{e\hbar}\left\langle \sum_{j=1}^{n}\gamma^0(j)\gamma^5(j)\,\vec{p}(j)^{\,2}\right\rangle_{\psi(0)} \approx 78\left[\frac{\text{GV}}{\text{cm}}\right]$$



Model	$\|d_e\|[e \cdot cm]$
Standard model	$< 10^{-38}$
Left-right symmetric	$10^{-28} \ldots 10^{-26}$
Lepton-flavor changing	$10^{-29} \ldots 10^{-26}$
Multi-Higgs	$10^{-28} \ldots 10^{-27}$
Supersymmetric	$\leq 10^{-25}$
Experimental limit (Tl)[32]	$< 1.6 \cdot 10^{-27}$
Experimental limit (YbF)[33]	$< 10.5 \cdot 10^{-28}$
Experimental limit (ThO)[34]	$< 1.1 \cdot 10^{-29}$

---

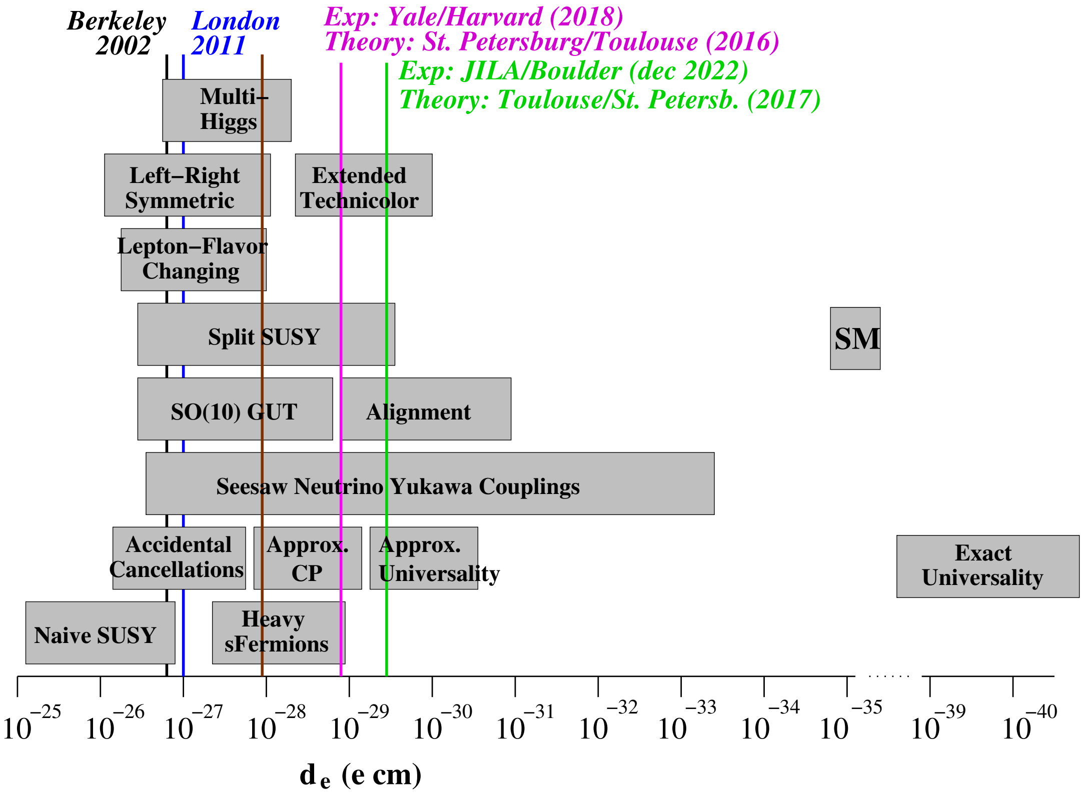
[31] D. DeMille (2005), H. Nataraj (2009)

[32] B.C. Regan, E.D. Commins, C.J. Schmidt, D.P. DeMille, *Phys Rev Lett* **88** (2002) *071805/1*

[33] J.J. Hudson, D.M. Kara, I.J. Smallman, B.E. Sauer, M.R. Tarbutt, E.A. Hinds, *Nature* **473** (2011) *493*

[34] ACME Collaboration, *Nature* **562** (2018) *355*; ACME, *Science* **6168** (2014) *269*; TF and M. K. Nayak, *J. Mol. Spectrosc.* **300** (2014) *16*; L. V. Skripnikov, A. N. Petrov, A. V. Titov, *J. Chem. Phys.* **139** (2013) *221103*; L. V. Skripnikov, A. V. Titov, *J. Chem. Phys.* **142** (2015) *024301*; M. Denis, TF, *J Chem Phys* **145** (2016) *214307*

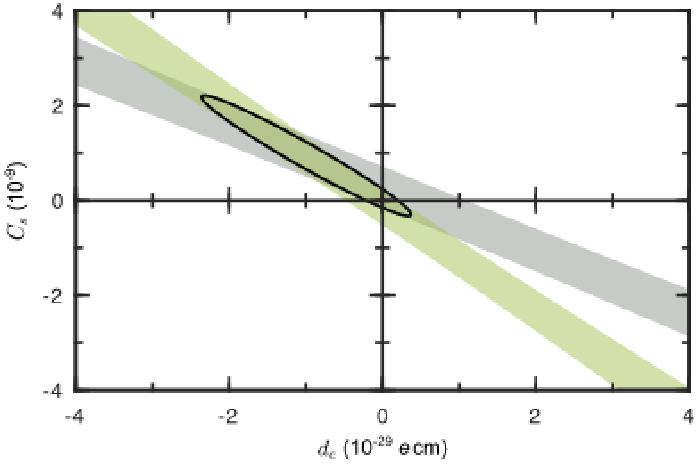
Updates: eEDM Constraint on BSM Theories (2023)



$E_{\text{eff}}\ \left[\frac{\text{GV}}{\text{cm}}\right]$

$22.7^{35}\quad 22.5^{36}$

$|d_e| < 4.1 \times 10^{-30}\, e\text{cm}\ (90\%\ \text{C.L.})^{37}$



Combination with ThO measurement[38]:

$|d_e| < 2.1 \times 10^{-29}\, e\text{cm}\ (90\%\ \text{C.L.})^{37}$

$|C_S| < 1.9 \times 10^{-9}\ (90\%\ \text{C.L.})^{37}$

---

[35] T. F., *Phys. Rev. A* **96** (2017) *040502(R)*

[36] L. V. Skripnikov, *J. Chem. Phys.* **147** (2017) *021101*

[37] T. S. Roussy, L. Caldwell, T. Wright, W. B. Cairncross, Y. Shagam, K. B. Ng, N. Schlossberger, S. Y. Park, A. Wang, J. Ye, E. A. Cornell, *Science* **381** (2023) *46*

[38] ACME Collaboration, *Nature* **562** (2018) *355*

Current World Records

In the presence of a non-zero EDM d, the system's Hamiltonian is
$\hat{H} = -\left(\mu\mathbf{B} + d\mathbf{E}\right) \cdot \frac{\hat{\mathbf{J}}}{|J|}$

- **"Paramagnetic" systems**: Precession measurement on **HfF$^+$**
  JILA group; Ye, Cornell[39]
  measured $f = (-14.6 \pm 29.7)\ \mu\text{Hz} \Rightarrow |d_e| \leq 4.1 \times 10^{-30}\, e$ cm
- **"Diamagnetic" systems**: Precession measurement on **Hg**
  Seattle group; Heckel[40]
  measured $|d_{Hg}| \leq 7.4 \times 10^{-30}\, e$ cm
- **Neutron** (n) EDM experiment
  PSI, Switzerland[41]
  measured $|d_n| \leq 1.8 \times 10^{-26}\, e$ cm

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[39] T. S. Roussy, *et al.*, J. Ye, E. A. Cornell, Science **381** (2023) *46*

[40] B. Graner *et al.*, Phys Rev Lett **116** (2016) *161601*

[41] C. Abel *et al.*, Phys. Rev. Lett., **124** (2020) *081803*

EDM Science

- Nuclear Schiff-moment interactions (Xe, Hg, TlF, FrAg et al.)

  A. Marc., M. Hubert, T. F., arXiv: 2309.11633 [physics.atom-ph] (2023)

  M. Hubert, T. F., *Phys. Rev. A* **106** (2022) *022817*

- Weak neutral current interactions (Xe, Hg, Ra, TlF)

  T. F., arXiv: 2311.06376 [physics.atom-ph] (2023)

  T. F., *Phys. Rev. A* **99** (2019) *012515*

- Electron EDM interactions (HfF^+, ThO, Hg, Tl, TaO^+, RaAg et al.)

  T. F., D. DeMille, *New J. Phys.* **23** (2021) *113039*

  T. F., L. V. Skripnikov, *Symmetry* **12** (2020) *498*

  T. F., M. Jung, *J High Energy Phys. (JHEP)* **07** (2018) *012*

  T. F., *Phys. Rev. A* **96** (2017) *040502(R)*

  T. F., *Phys. Rev. A* **95** (2017) *022504*

  M. Denis, T. F., *J. Chem. Phys.* **145** (2016) *214307*

- Nuclear MQM interactions (TaN, TaO^+, HfF^+, RaAg)

  T. F., M. K. Nayak, M. G. Kozlov, *Phys. Rev. A* **93** (2016) *012505*

EDM Science

- Nuclear Schiff-moment interactions (Xe, Hg, TlF, FrAg et al.)

  A. Marc., M. Hubert, T. F., arXiv: 2309.11633 [physics.atom-ph] (2023)

  M. Hubert, T. F., *Phys. Rev. A* **106** (2022) *022817*

- Weak neutral current interactions (Xe, Hg, Ra, TlF)

  T. F., arXiv: 2311.06376 [physics.atom-ph] (2023)

  T. F., *Phys. Rev. A* **99** (2019) *012515*

- Electron EDM interactions (HfF^+, ThO, Hg, Tl, TaO^+, RaAg et al.)

  T. F., D. DeMille, *New J. Phys.* **23** (2021) *113039*

  T. F., L. V. Skripnikov, *Symmetry* **12** (2020) *498*

  T. F., M. Jung, *J High Energy Phys. (JHEP)* **07** (2018) *012*

  T. F., *Phys. Rev. A* **96** (2017) *040502(R)*

  T. F., *Phys. Rev. A* **95** (2017) *022504*

  M. Denis, T. F., *J. Chem. Phys.* **145** (2016) *214307*

- Nuclear MQM interactions (TaN, TaO^+, HfF^+, RaAg)

  T. F., M. K. Nayak, M. G. Kozlov, *Phys. Rev. A* **93** (2016) *012505*

Search for a Lepton EDM: Radium-Silver (RaAg)

in collaboration with

David DeMille

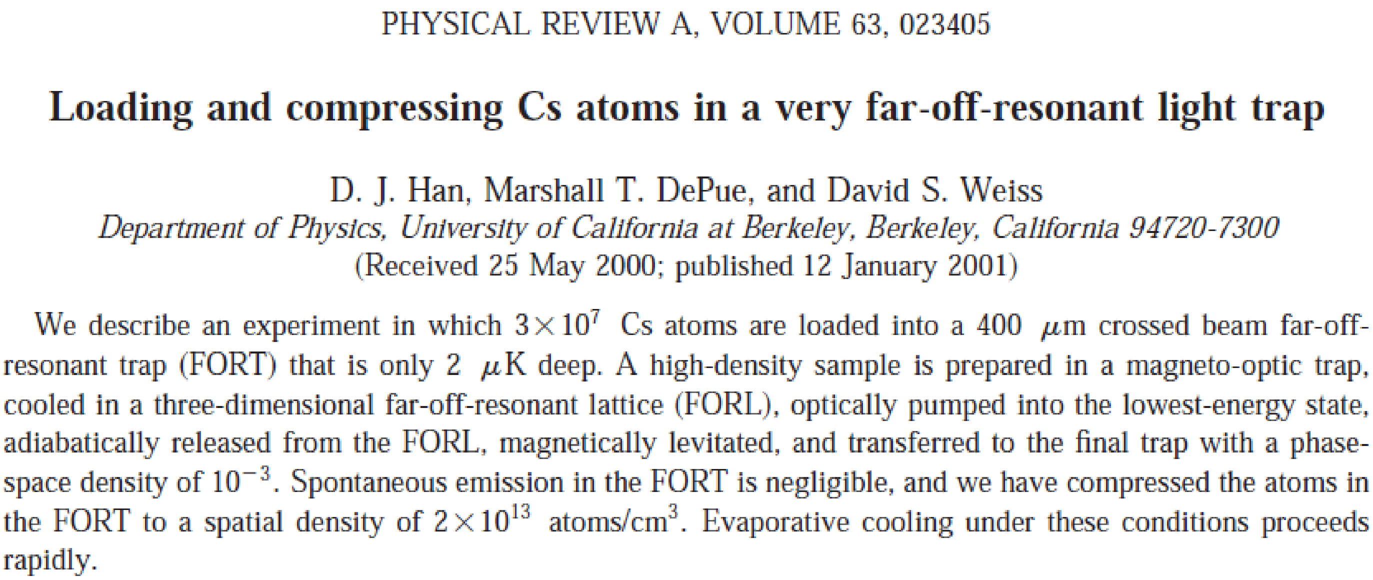
Yale University / University of Chicago

Olivier Grasdijk

ARGONNE Labs / University of Chicago

Montpellier Seminar, 5 December 2023

Going Ultracold: From beams to traps



PHYSICAL REVIEW A, VOLUME 63, 023405

Loading and compressing Cs atoms in a very far-off-resonant light trap

D. J. Han, Marshall T. DePue, and David S. Weiss
Department of Physics, University of California at Berkeley, Berkeley, California 94720-7300
(Received 25 May 2000; published 12 January 2001)

We describe an experiment in which 3×10^7 Cs atoms are loaded into a 400 μm crossed beam far-off-resonant trap (FORT) that is only 2 μK deep. A high-density sample is prepared in a magneto-optic trap, cooled in a three-dimensional far-off-resonant lattice (FORL), optically pumped into the lowest-energy state, adiabatically released from the FORL, magnetically levitated, and transferred to the final trap with a phase-space density of 10^{-3}. Spontaneous emission in the FORT is negligible, and we have compressed the atoms in the FORT to a spatial density of 2×10^{13} atoms/cm^3. Evaporative cooling under these conditions proceeds rapidly.

- Estimated sensitivity of Cs EDM measurement in DLT[42] is $|d_e| \approx 10^{-29}\,e\text{cm}$

Cs atom: $\Delta E = R\,E_{\text{ext}}\,d_e$
$E_{\text{int}} \approx 20\ \left[\frac{\text{MV}}{\text{cm}}\right]$

Ultracold **XY** Molecule: $\Delta E = E_{\text{eff}}\,d_e$
$E_{\text{eff}} \approx 50\ \left[\frac{\text{GV}}{\text{cm}}\right]$

- A factor of $\approx \mathbf{2500}$ gain in sensitivity!

---

[42] DLT: Dipole light trap; D. Weiss (Penn State), 2014: “Measuring the eEDM using laser-cooled Cs atoms in optical lattices”
S. Chu, J.E. Bjorkholm, A. Ashkin, A. Cable, *Phys. Rev. Lett.* **57** (1986) *314*
C. Chin, V. Leiber, V. Vuletić, A.J. Kerman, S. Chu, *Phys. Rev. A* **63** (2001) *033401*

Towards Ultracold DLT EDM Measurement[43]

Picking the cherry

Target atom:

$Z(\text{Ra}) = 88$ $\alpha_D(\text{Ra}) = 246 \pm 4$ a.u.[44]

Polarizing partner:

Alkali(-like) atoms: Li, Na, K, Rb, Cs, Fr; Cu, Ag, Au

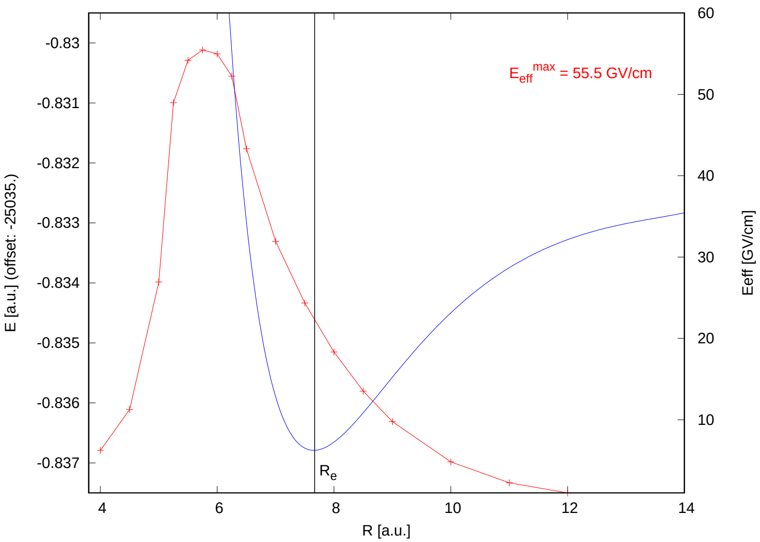
	R_e [a.u.]	B_e [cm^{-1}]	D[Debye]	EA [eV]	E_{eff} $\left[\frac{\text{GV}}{\text{cm}}\right]$	W_S [kHz]	E_{pol} $\left[\frac{\text{kV}}{\text{cm}}\right]$
RaLi	7.668	0.151	1.36	0.618	22.2	-59.5	13.3
RaNa	8.703	0.038	0.51	0.548	12.0	-32.2	8.90
RaK	10.37	0.017	0.39	0.501	5.44	-14.6	5.18
RaRb	10.75	0.008	0.36	0.486	5.01	-13.6	2.75
RaCs	11.25	0.006	0.46	0.472	4.52	-12.6	1.48
RaFr	11.26	0.004	0.24	0.486	3.44	-12.4	2.06
RaCu	6.050	0.033	**4.30**	**1.236**	67.0	-180.6	0.92
RaAg	6.241	0.021	**4.76**	**1.304**	**63.9**	**-175.1**	0.53
RaAu	5.836	0.017	**5.71**	**2.309**	50.4	-166.4	0.36

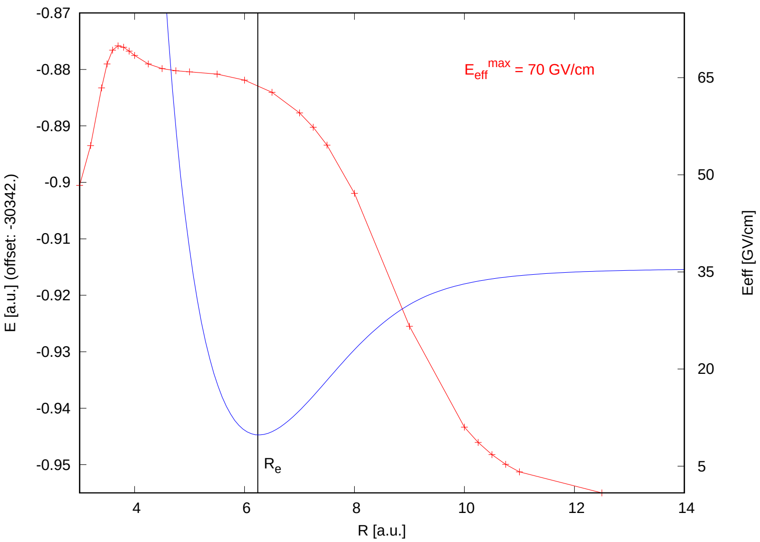
---

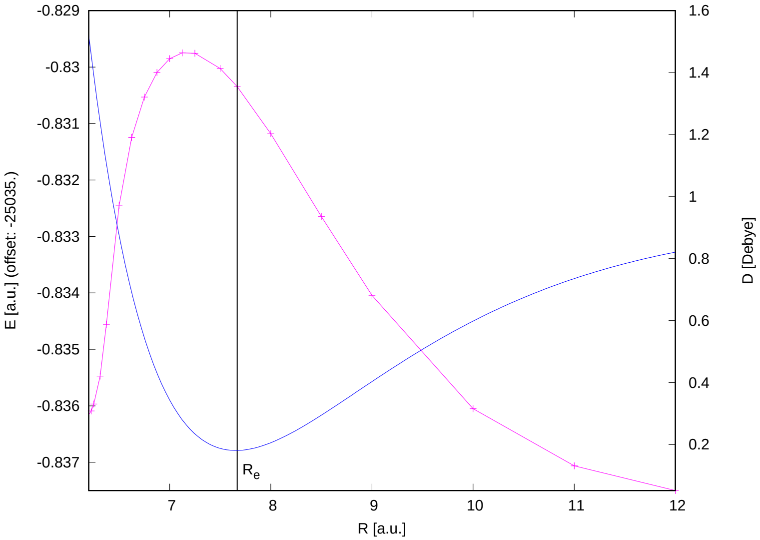
[43] T. F., D. DeMille, *New J. Phys.* **23** (2021) *113039*

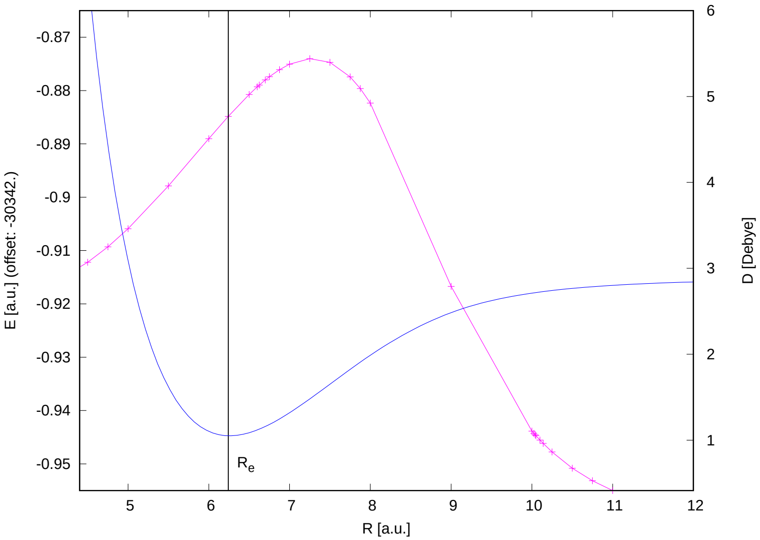
[44] P. Schwerdtfeger, J. K. Nagle, *Mol. Phys.* **117** (2019) *1200*

RaLi vs. RaAg[45]









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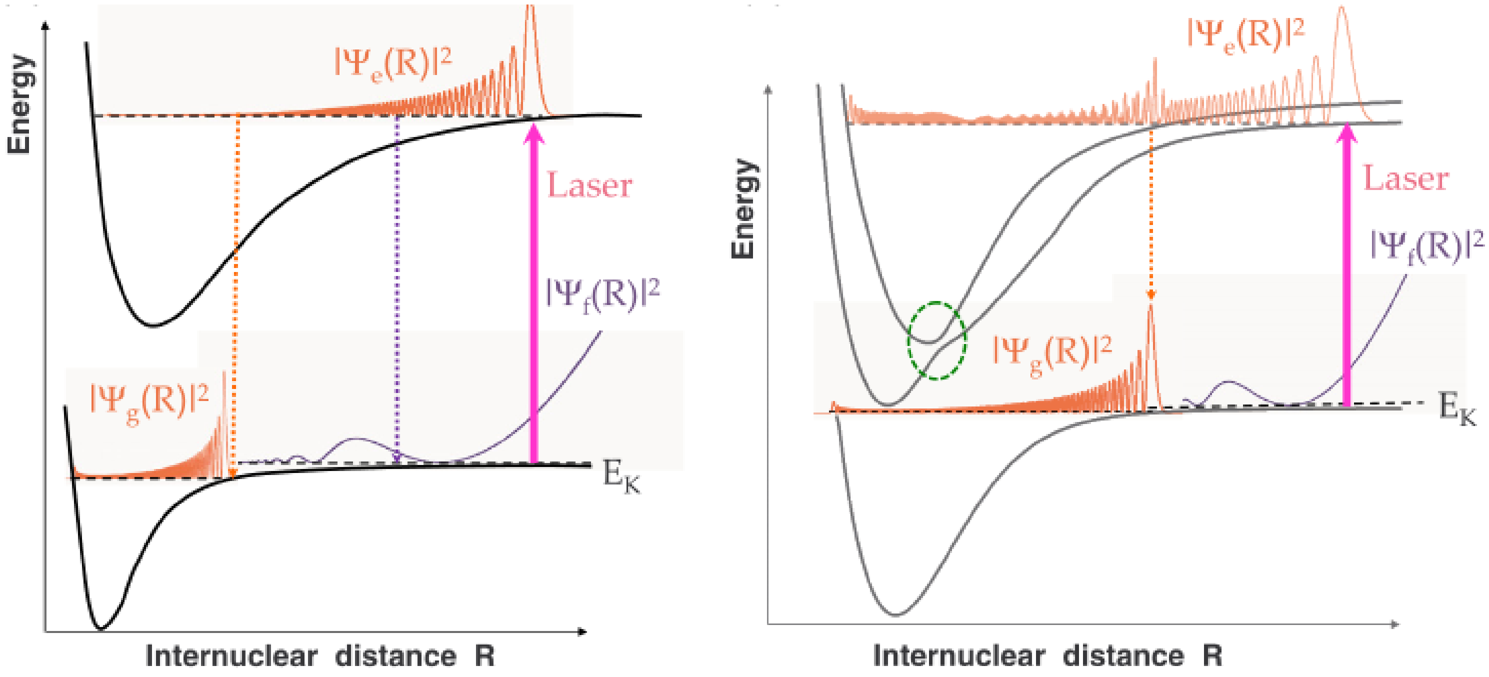
[45] T. F., D. DeMille, *New J. Phys.* **23** (2021) *113039*

“Building” RaAg in a DLT EDM Experiment

- Photoassociating ultracold atoms into ultracold molecules[46]



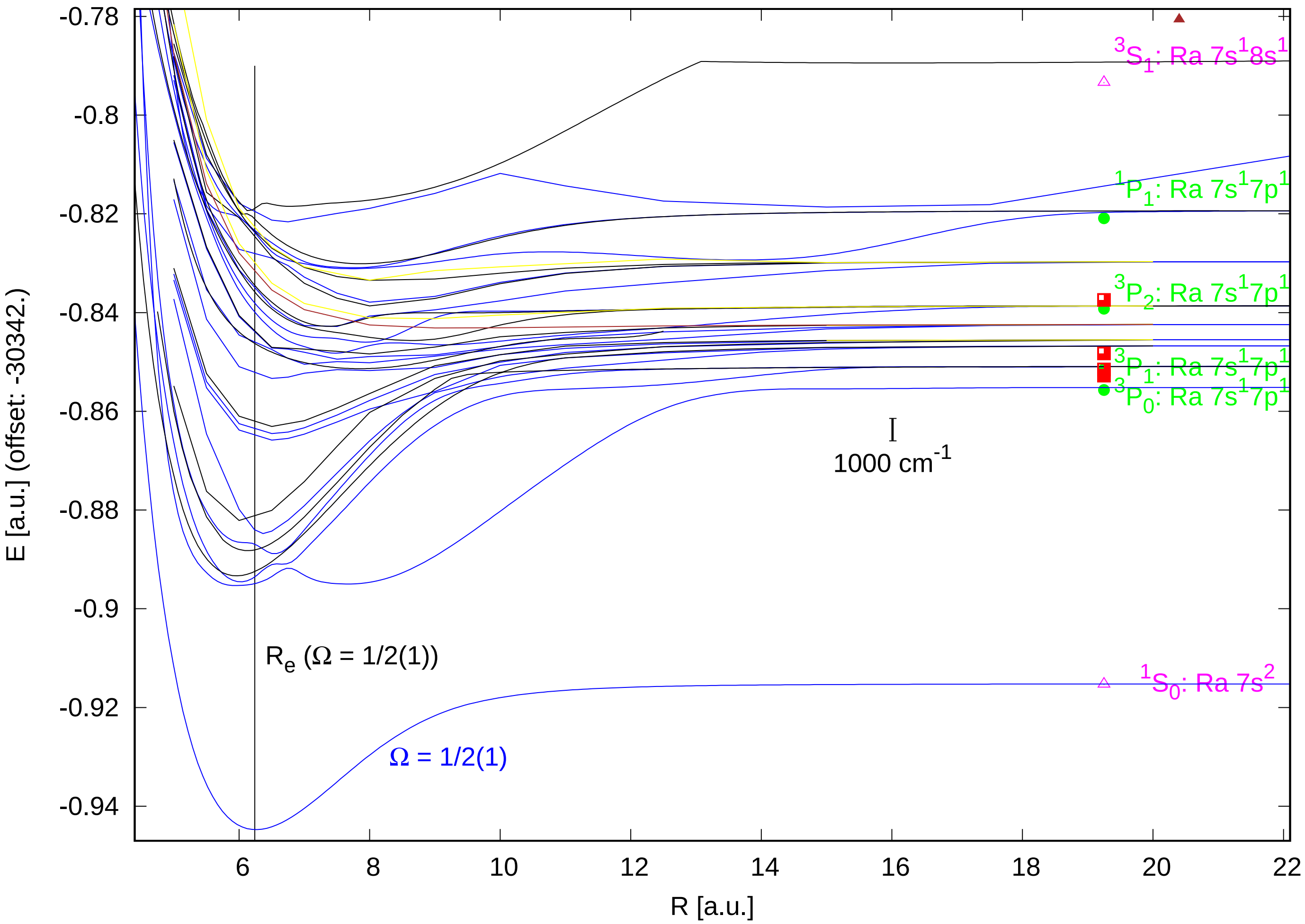
- Does its electronic spectrum allow for efficient energy transfer (remove binding energy without heating) ?

- Which states are candidates for photoassociation ?

---

[46] L. D. Carr, D. DeMille, R. V. Krems, J. Ye, *New J. Phys.* **11** (2009) *055049*

RaAg: Complete Spectrum up to $T \approx 5$ eV



$D_e(1/2(1)) \approx 0.83$ eV

D_e(KRb) ≈ 0.52 eV[47]

D_e(YbRb) ≈ 0.11 eV[48]

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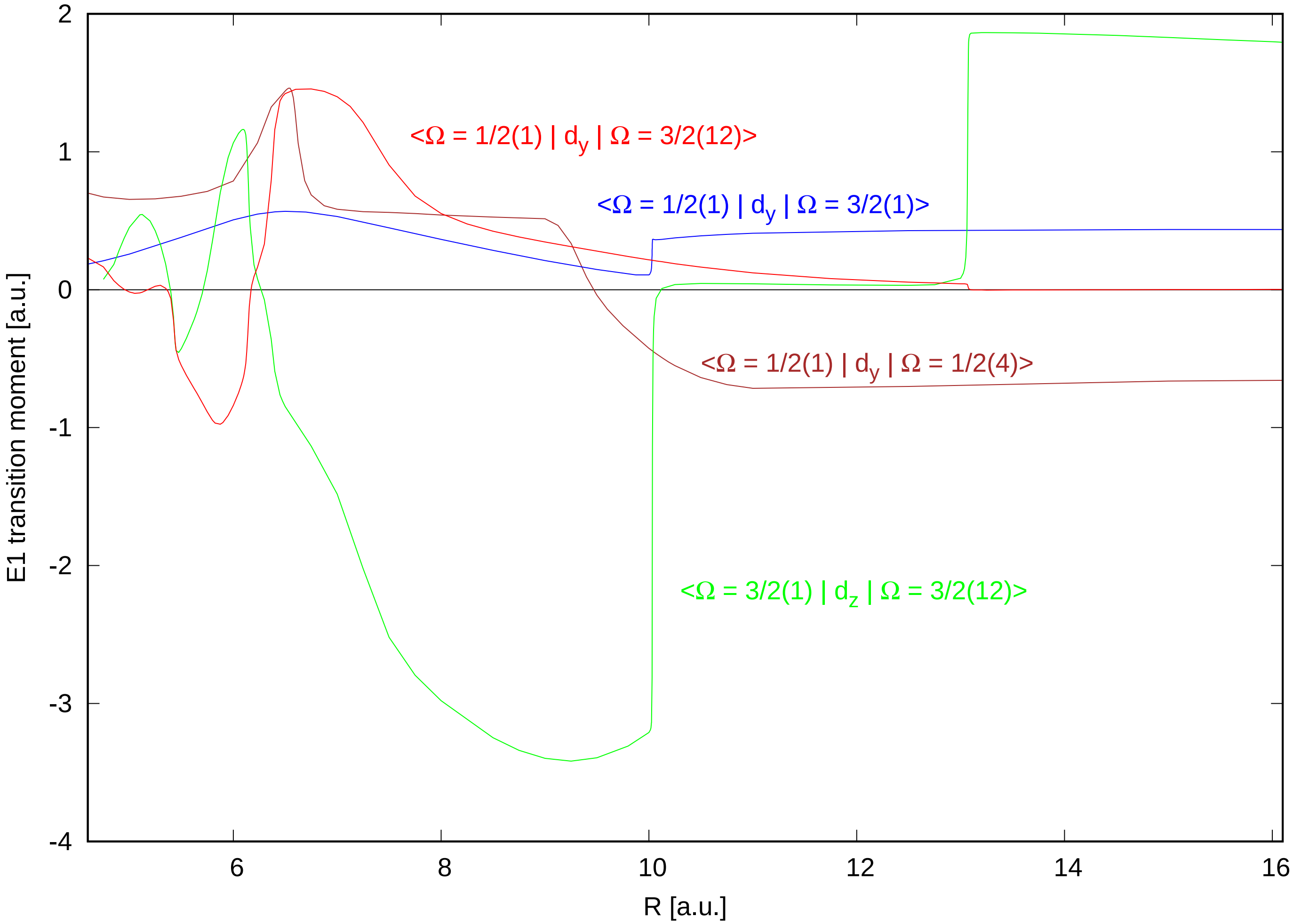
[47] S. Kasahara, C. Fujiwara, N. Okada, H. Katô, M. Baba, *J. Chem. Phys.* **111** (1999) *8857*

[48] L. K. Sørensen, S. Knecht, T. F., C. M. Marian, *J. Phys. Chem A* **113** (2009) *12607*

RaAg[49]**: E1 TDM** $d_{XY}(R) = \left\langle \Psi_X \middle| \sum_j q_j\, \hat{\mathbf{r}}_j \middle| \Psi_Y \right\rangle (R)$



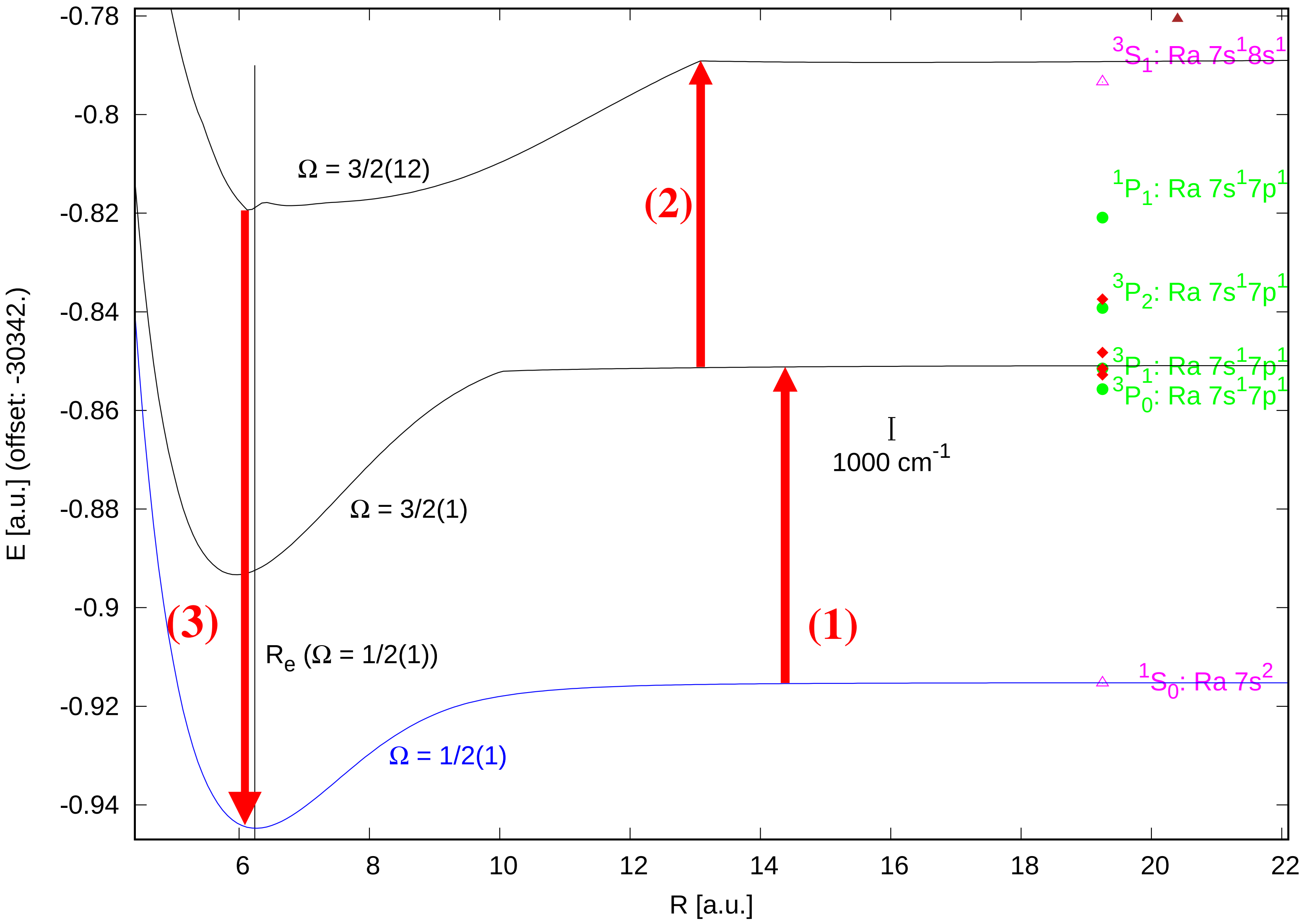
Then: $d_{v,v'} = \int_R \psi_{vX}(R)\; d_{XY}(R)\; \psi_{v'Y}(R) dR$

---

[49] O. Grasdijk, T. Fleig, D. DeMille (2023) *in preparation.*

RaAg

A Pathway To Assemble RaAg (X) from Trapped Ra-Ag Atom Pairs



Long-Range Theory

Van der Waals interaction potential for two neutral heteronuclear atoms:

$$V(R) = -\frac{C_6}{R^6} - \frac{C_8}{R^8} - \frac{C_{10}}{R^{10}} - \dots$$

Porsev formalism[50]:

$$C_6(\Omega) = \sum_{j=|J_A-1|}^{J_A+1} \sum_{J=|J_B-1|}^{J_B+1} A_{jJ}(\Omega)\, X_{jJ}$$

with

$$A_{jJ}(\Omega) = \sum_{\mu m M_J} \left\{ (1+\delta_{\mu 0}) \begin{pmatrix} J_A & 1 & j \\ -M_{J_A} & \mu & m_j \end{pmatrix} \begin{pmatrix} J_B & 1 & J \\ -M_{J_B} & -\mu & M_j \end{pmatrix} \right\}^2$$

$$\begin{pmatrix} j_1 & j_2 & j \\ m_{j_1} & m_{j_2} & m_j \end{pmatrix} = \frac{\left\langle j_1 j_2 m_{j_1} m_{j_2} | j_1 j_2 j\, -m_j \right\rangle}{(-1)^{-j_1+j_2+m_j}\sqrt{2j+1}}$$

$$X_{jJ} = \sum_{\alpha_l, \alpha_k} \frac{\left| \left\langle \alpha_A\, J_A || \hat{T}^{(1)} || \alpha_l\, J_l = j \right\rangle \right|^2 \left| \left\langle \alpha_B\, J_B || \hat{T}^{(1)} || \alpha_k\, J_k = J \right\rangle \right|^2}{E_l - E_A + E_k - E_B}$$

$$\left\langle \alpha\, J || \hat{\boldsymbol{D}} || \alpha'\, J' \right\rangle = \frac{\left|\left| \left\langle \alpha\, J\, M_J | \hat{\boldsymbol{D}} | \alpha'\, J'\, M'_J \right\rangle \right|\right| \sqrt{2J+1}}{\left\langle J'\, 1\, M'_J\, q | J'\, 1\, J\, M_J \right\rangle}$$

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[50] S. G. Porsev, M. S. Safronova, A. Derevianko, and C. W. Clark, *Phys. Rev. A* **89** (2014) *022703*

Long-Range Interactions

E1 Transitions in Earth-Alkaline and Alkali Test Systems

$\left|\left\langle X\left(J=\frac{1}{2}\right)||\hat{\boldsymbol{D}}||l\left(J=\frac{1}{2}\right)\right\rangle\right|$ and $\left|\left\langle X\left(J=\frac{1}{2}\right)||\hat{\boldsymbol{D}}||l\left(J=\frac{3}{2}\right)\right\rangle\right|$ in [a.u.]

Li	present			experiment [51]	literature
Excited state	RME	$\Delta\varepsilon$ [cm^{-1}]	f	$\Delta\varepsilon$ [cm^{-1}]	f
$^2P_{1/2}(2p^1)$	3.3197	14909	0.2495	14903.66	
$^2P_{3/2}(2p^1)$	4.6948	14910	0.4991	14904.00	$0.7470\,(^2P)$ [52]
$^2P_{1/2}(3p^1)$	0.1794	30916	0.0015	30925.38	
$^2P_{3/2}(3p^1)$	0.2536	30917	0.0030	30925.38	$0.00482\,(^2P)$ [53]

$\left|\left\langle X(J=0)||\hat{\boldsymbol{D}}||l(J=1)\right\rangle\right|$ [a.u.]

Be	present			experiment [51]	literature
excited state	RME	$\Delta\varepsilon$ [cm^{-1}]	f	$\Delta\varepsilon$ [cm^{-1}]	f
$^3P_1(2s^12p^1)$	0.0002	21977	0.0000	21978.93	
$^1P_1(2s^12p^1)$	3.2615	42585	1.3760	42565.35	1.374 [54]
$^1P_1(2s^13p^1)$	0.2111	60347	0.0082	60187.34	0.0086 [54]

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[51] A. Kramida, Yu. Ralchenko, J. Reader, and and NIST ASD Team, *NIST Atomic Spectra Database* (2019)

[52] Z.-C. Yan, M. Tambasco, and G. W. F. Drake, *Phys. Rev. A* **57** (1998) *1652*

[53] L. Qu, Z. Wang, and B. Li, *Eur. Phys. J. D* **5** (1999) *173*

[54] S. Nasiri, L. Adamowicz, and S. Bubin, *J. Phys. Chem. Ref. Data* **50** (2021) *043107*

Long-Range Interactions

Earth-Alkali Atoms

$$\left|\left\langle X(J=0)||\hat{\boldsymbol{D}}||l(J=1)\right\rangle\right|$$ [a.u.]

Ca		present			experiment		
state	CI model	RME	$\Delta\varepsilon$ [cm^{-1}]	f	RME	$\Delta\varepsilon$ [cm^{-1}] [55]	f
$^1P_1(4p^1)$(3)	SDTQ_SD	4.98	25200	1.90	4.912^*	23652.304	$1.7332(7)$[56]
$^1P_1(5p^1)$(10)	SDTQ_SD	0.23	43000	0.01		36731.615	
$^1P_1(6p^1)$(17)	SDTQ_SD	0.93	52400	0.14		41679.008	

Dispersion coefficients for RaAg valence-isoelectronic systems:

	C_6 [a.u.]	
System	present	literature
BeLi $X^2\Sigma_{1/2}$	464	478 a[56]
CaLi $X^2\Sigma_{1/2}$	1581 1644^*	1689
CaCa $X(\Omega=0)$	2030^*	$2080(7)$ b[56]

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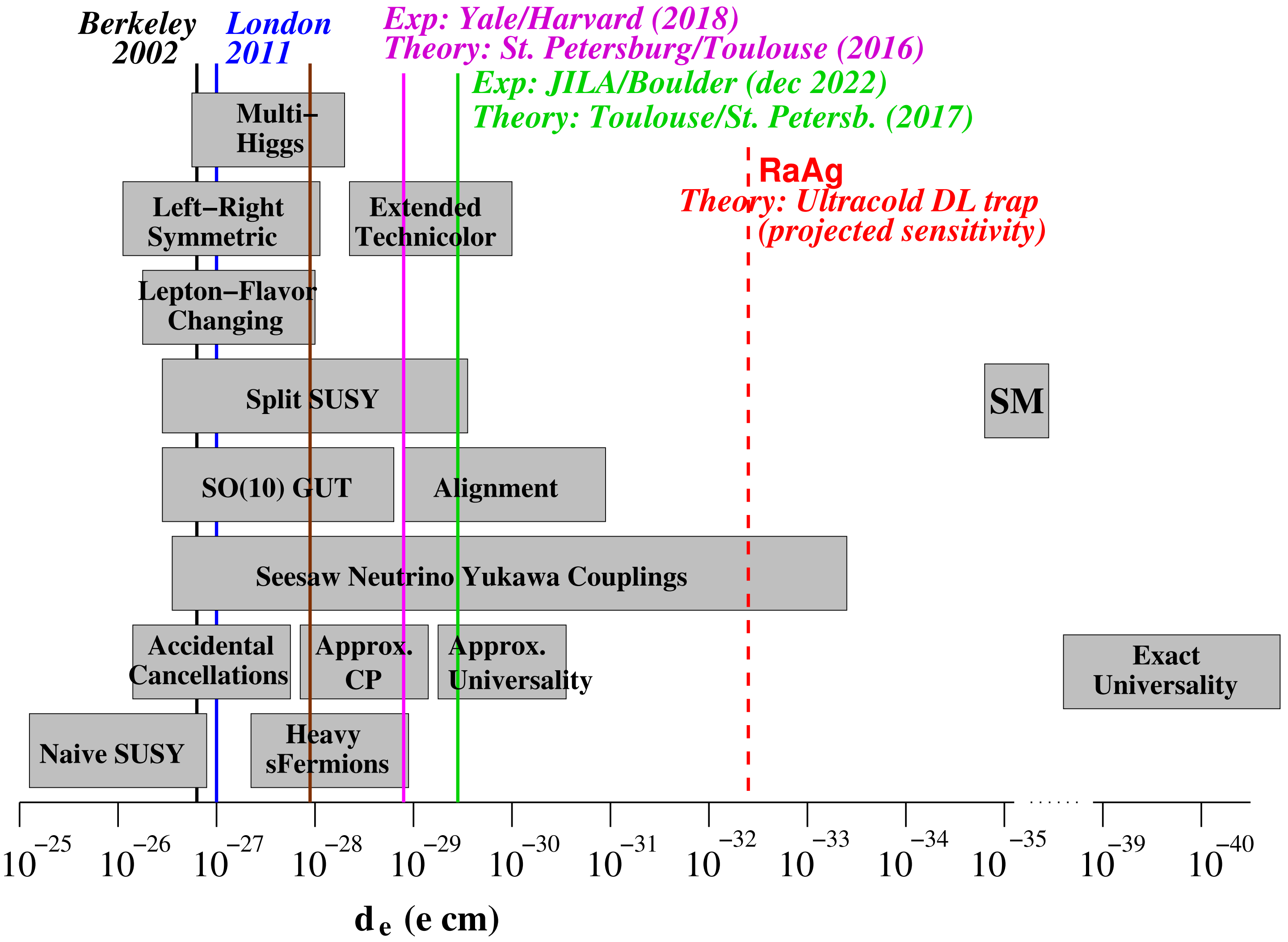
[55] A. Kramida, Yu. Ralchenko, J. Reader, and and NIST ASD Team, *NIST Atomic Spectra Database* (2021)

[56] (a) J. Jiang, Y. Cheng, and J. Mitroy, *J. Phys. B: At. Mol. Opt. Phys.* **46** (2013) *134305*
(b) O. Allard, C. Samuelis, A. Pashov, H. Knöckel, and E. Tiemann, *Eur. Phys. J. D* **26** (2003) *155*

eEDM Constraint on Beyond-Standard-Model Theories

Single-source interpretation (21??)



People

Mickaël Hubert, Lecturer

Aurélien Marc, PhD Student

Thanks for your attention !

EDM Science

- Nuclear Schiff-moment interactions (Xe, Hg, TlF, FrAg et al.)

  A. Marc., M. Hubert, T. F., arXiv: 2309.11633 [physics.atom-ph] (2023)

  M. Hubert, T. F., *Phys. Rev. A* **106** (2022) *022817*

- Weak neutral current interactions (Xe, Hg, Ra, TlF)

  T. F., arXiv: 2311.06376 [physics.atom-ph] (2023)

  T. F., *Phys. Rev. A* **99** (2019) *012515*

- Electron EDM interactions (HfF^+, ThO, Hg, Tl, TaO^+, RaAg et al.)

  T. F., D. DeMille, *New J. Phys.* **23** (2021) *113039*

  T. F., L. V. Skripnikov, *Symmetry* **12** (2020) *498*

  T. F., M. Jung, *J High Energy Phys. (JHEP)* **07** (2018) *012*

  T. F., *Phys. Rev. A* **96** (2017) *040502(R)*

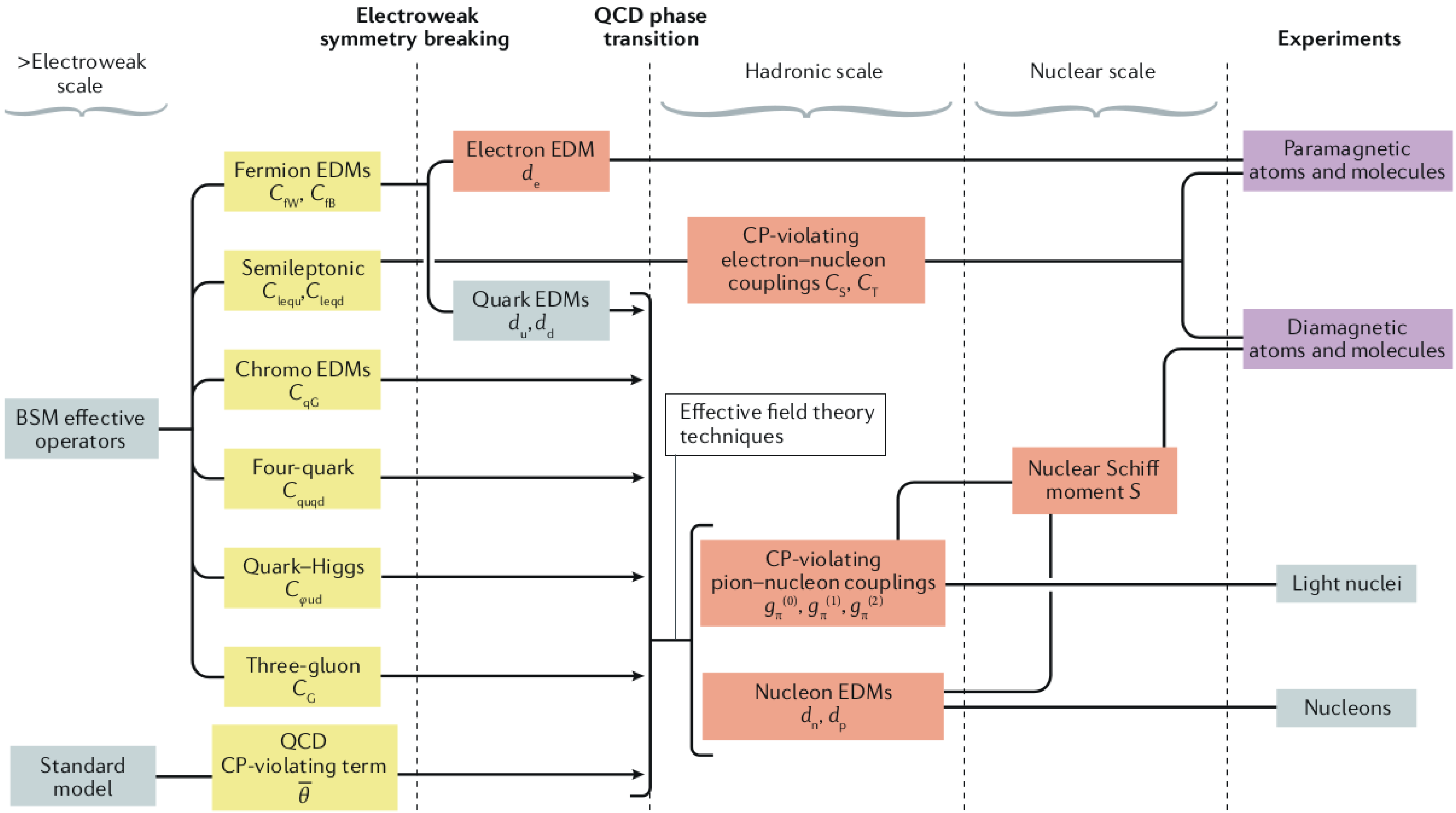
  T. F., *Phys. Rev. A* **95** (2017) *022504*

  M. Denis, T. F., *J. Chem. Phys.* **145** (2016) *214307*

- Nuclear MQM interactions (TaN, TaO^+, HfF^+, RaAg)

  T. F., M. K. Nayak, M. G. Kozlov, *Phys. Rev. A* **93** (2016) *012505*

EDMs and their possible sources: An overview



Electroweak symmetry breaking

QCD phase transition

Experiments

>Electroweak scale

Hadronic scale

Nuclear scale

Fermion EDMs C_{fW}, C_{fB}

Semileptonic C_{lequ},C_{leqd}

Chromo EDMs C_{qG}

BSM effective operators

Four-quark C_{quqd}

Quark–Higgs $C_{\varphi ud}$

Three-gluon C_G

Standard model

QCD CP-violating term $\bar{\theta}$

Electron EDM d_e

Quark EDMs d_u, d_d

CP-violating electron–nucleon couplings C_S, C_T

Effective field theory techniques

CP-violating pion–nucleon couplings $g_\pi^{(0)}$, $g_\pi^{(1)}$, $g_\pi^{(2)}$

Nucleon EDMs d_n, d_p

Nuclear Schiff moment S

Paramagnetic atoms and molecules

Diamagnetic atoms and molecules

Light nuclei

Nucleons

W. Cairncross, J. Ye, *Nat. Rev. Phys.* **1** (2019) *510*

Tensor-Pseudotensor $\mathcal{P}$,$\mathcal{T}$-odd Nucleon-Electron Interaction

Effective Hamiltonian for a single electron[57] for Ne neutral weak current

$$\hat{H}^{\text{eff}}_{\text{T-PT-ne}} = \frac{\imath G_F}{\sqrt{2}} \sum_N C_T^N \, \rho_N(\mathbf{r}) \gamma^0 \sigma_{N\,\mu\nu} \gamma^5 \sigma^{\mu\nu}$$

Using the identity

$$\sigma_{N\,\mu\nu}\gamma^5\sigma^{\mu\nu} = 2\gamma_N^0 \boldsymbol{\gamma}_N \cdot \boldsymbol{\Sigma} + 2\gamma^0 \boldsymbol{\Sigma}_N \cdot \boldsymbol{\gamma}$$

and $\langle\psi|\boldsymbol{\Sigma}|\psi\rangle = 0$ for closed-shell systems:

$$\hat{H}^{\text{eff}}_{\text{T-PT-ne}} = \frac{\imath G_F}{\sqrt{2}} \sum_N 2C_N^T \, \boldsymbol{\Sigma}_N \cdot \boldsymbol{\gamma} \rho_N(\mathbf{r})$$

For nuclear state $|I, M_I = I\rangle$ isotope-specific many-electron Hamiltonian[58]:

$$\hat{H}^{\text{eff}}_{\text{T-PT-ne}} = \imath\sqrt{2} G_F \, C_T^A \, \langle\Sigma\rangle_A \sum_{j=1}^{n} (\gamma_3)_j \, \rho(\mathbf{r}_j)$$

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[57] K. Yanase, N. Yoshinaga, K. Higashiyama, N. Yamanaka *Phys. Rev. D* **99** (2019) *075021*

[58] T. F., M. Jung *Phys. Rev. A* **103** (2021) *012807*

Molecular T-PT-ne Interaction Constant[57]

Energy shift of state E in a molecule:

$$\Delta\varepsilon_E = \left\langle \psi_E^{(0)} \middle| \hat{H}^{\text{eff}}_{\text{T-PT-ne}} \middle| \psi_E^{(0)} \right\rangle = W_T \, C_T^A$$

It then follows that

$$W_T(X) = \sqrt{2} G_F \langle \Sigma \rangle_A \left\langle \psi_E^{(0)} \middle| \imath \sum_{j=1}^{n} \left(\gamma_3\right)_j \, \rho_X(\mathbf{r}_j) \middle| \psi_E^{(0)} \right\rangle$$

In atoms

$$d_a = C_T^A \, \alpha_{C_T}$$

where

$$\alpha_{C_T} := \frac{\left\langle \hat{H}^{\text{eff}}_{\text{T-PT-ne}} \right\rangle_{\psi^{(0)}(E_{\text{ext}})}}{E_{\text{ext}}}$$

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[57] T. F., *arXiv: 2311.06376 [physics.atom-ph]* (2023)

W_T(Tl) in TlF($^1\Sigma_0$) from Hartree-Fock theory[58]

model	W_T(Tl) [kHz $\langle\Sigma\rangle_A$]	total energy
Hartree-Fock[1]	-0.851	
Dirac-Coulomb HF[2]	-4.330	-20374.4108
DZ/DCHF	-4.601	-20374.41122770
TZ/DCHF	-4.673	-20374.46576781
QZ/DCHF	-4.684	-20374.47704191
QZ+dens+sp/DCHF	-4.684	-20374.47660904

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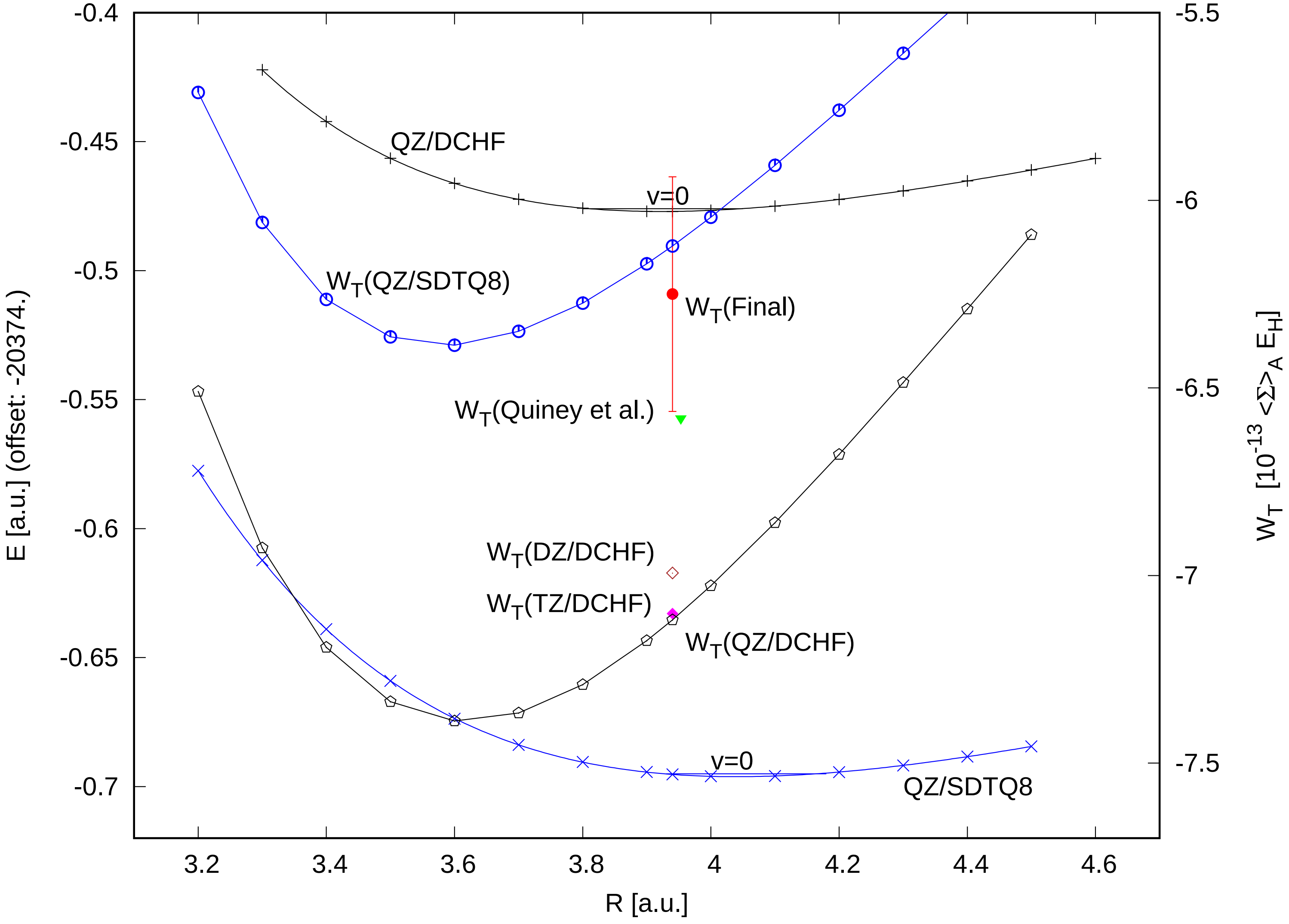
[58] T. F., *arXiv: 2311.06376 [physics.atom-ph]* (2023)

[1] D. Cho and K. Sangster and E. A. Hinds, *Phys. Rev. A* **44** (1991) *2783*
P. V. Coveney and P. G. H. Sandars, *J. Phys. B: At. Mol. Opt. Phys.* **16** (1983) *3727*

[2] H. M. Quiney, J. K. Lærdahl, T. Saue, and K. Fægri Jr., *Phys. Rev. A* **57** (1998) *920*

W_T(Tl) in TlF($^1\Sigma_0$) from Correlated Theory[59]



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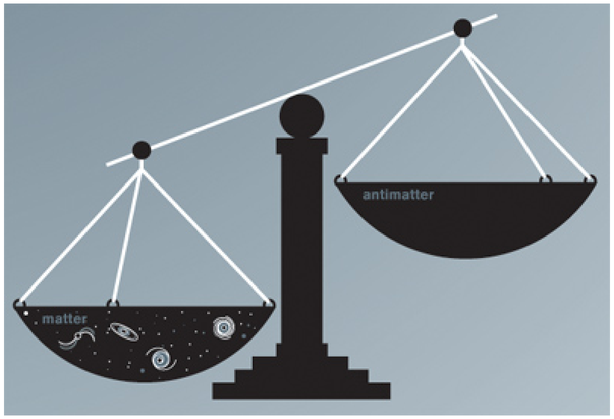
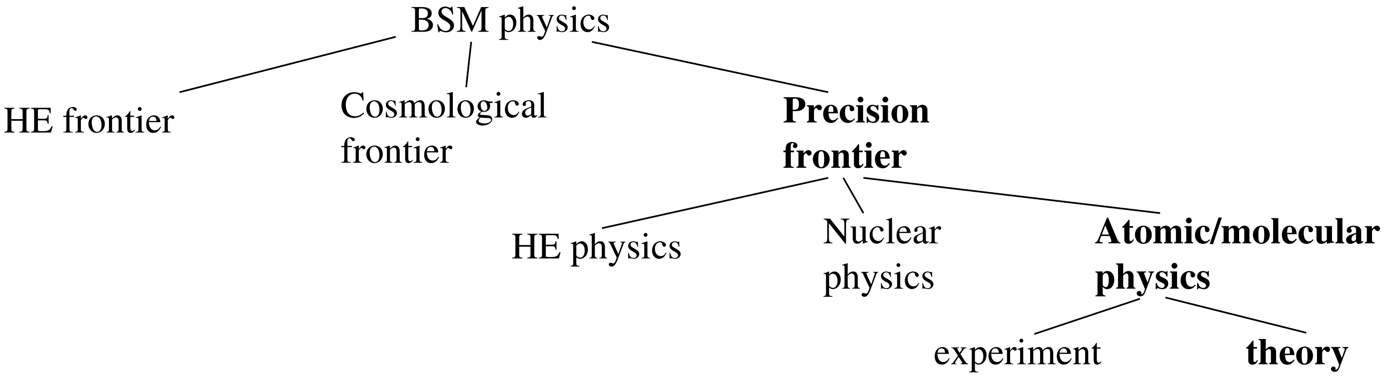
[59] T. F., *arXiv: 2311.06376 [physics.atom-ph]* (2023)

Questions Begging an Answer



- **Matter-antimatter asymmetry** of the universe[1]
- Nature of **cold dark matter**
- Degree of $\mathcal{CP}$ **violation** in nature[2]

- Detection/constraint of **EDMs** as a powerful probe[62]


BSM physics

HE frontier

Cosmological frontier

Precision frontier

HE physics

Nuclear physics

Atomic/molecular physics

experiment

theory

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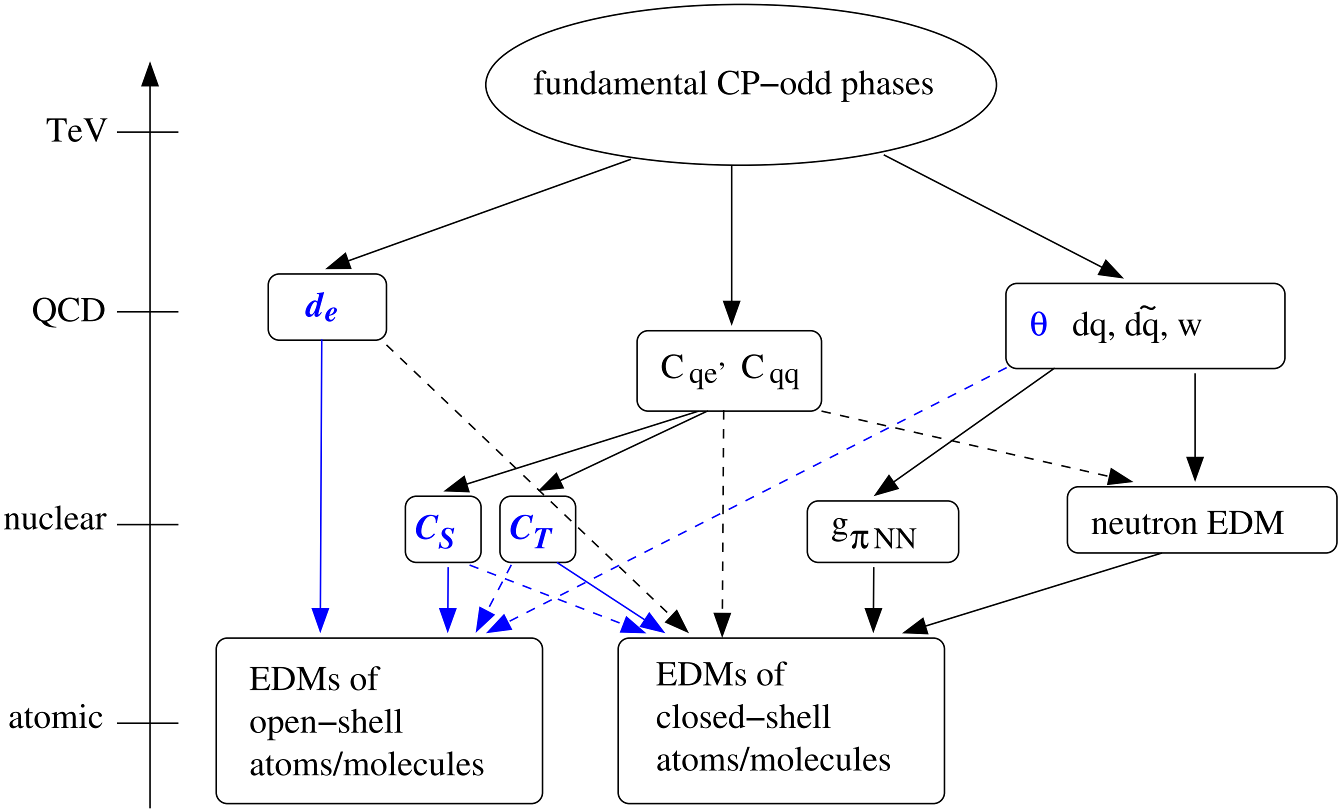
[1] M. Dine, A. Kusenko, *Rev. Mod. Phys.* **76** (2004) *1*

[2] G. C. Branco, R. G. Felipe, F. R. Joaquim, *Rev. Mod. Phys.* **84** (2012) *515*

[62] J. Engel, M.J. Ramsey-Musolf, U. van Kolck, *Prog. Part. Nuc. Phys.* **71** (2013) *21*
M. Safronova, D. Budker, D. DeMille, D.F. Jackson Kimball, A. Derevianko, C.W. Clark, *Rev. Mod. Phys.* **90** (2018) *025008*
T.E. Chupp, P. Fierlinger, M.J. Ramsey-Musolf, J.T. Singh, *Rev. Mod. Phys.* **91** (2019) *015001*

Electric Dipole Moments and Their Source Tree[63]



$d_{e,q}$: (electron, quark) EDM

$C_{S,P,T}$: Coupling constants of $\mathcal{CP}$-odd electron-nucleon interaction

θ: QCD "theta" term

- EDMs are low-energy physics probes of high-energy physics symmetry breaking

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[63] M. Pospelov, A. Ritz, "Electric dipole moments as probes of new physics", *Ann. Phys.* **318** (2005) *119*

Fundamental Discrete Symmetries

(P) Violation

The fall of $\mathcal{P}$ invariance[64]; measuring helicity $\boldsymbol{\sigma} \cdot \hat{\mathbf{p}}$ in weak decays

$$\begin{array}{ccccc} \mu^+ & & \pi^+ & & \nu_\mu \\ \binom{s_\mu}{\rightarrow} & \longleftarrow & s_\pi{=}0 & \longrightarrow & \binom{s_\nu}{\leftarrow} \\ \text{left-handed } \mu^+ & & & & \text{left-handed } \nu_\mu \\ & & \overset{\hat{\mathcal{P}}}{\longrightarrow} & & \\ \nu_\mu & & \pi^+ & & \mu^+ \\ \binom{s_\nu}{\leftarrow} & \longleftarrow & s_\pi{=}0 & \longrightarrow & \binom{s_\mu}{\rightarrow} \\ \text{right-handed } \nu_\mu & & & & \text{right-handed } \mu^+ \end{array}$$

$$\begin{array}{ccccc} \mu^- & & \pi^- & & \overline{\nu}_\mu \\ \binom{s_\mu}{\leftarrow} & \longleftarrow & s_\pi{=}0 & \longrightarrow & \binom{s_{\overline{\nu}}}{\rightarrow} \\ \text{right-handed } \mu^- & & & & \text{right-handed } \overline{\nu}_\mu \\ & & \overset{\hat{\mathcal{P}}}{\longrightarrow} & & \\ \overline{\nu}_\mu & & \pi^- & & \mu^- \\ \binom{s_{\overline{\nu}}}{\rightarrow} & \longleftarrow & s_\pi{=}0 & \longrightarrow & \binom{s_\mu}{\leftarrow} \\ \text{left-handed } \overline{\nu}_\mu & & & & \text{left-handed } \mu^- \end{array}$$

right-handed μ^+ or left-handed μ^- never observed

$\Rightarrow$ right-handed ν_μ and left-handed $\overline{\nu}_\mu$ do not exist.

$\Rightarrow$ $\mathcal{P}$ *maximally violated* in weak processes.

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[64] C. S. Wu et al., *Phys Rev* **105** (1957) *254*
G. Backenstoss et al., *Phys Rev Lett* **6** (1961) *415*
M. Bardon et al., *Phys Rev Lett* **7** (1961) *23*

Fundamental Discrete Symmetries

(CP) Conservation

Same weak decays under $(\hat{\mathcal{C}}\hat{\mathcal{P}})$ transformation:

$$\underset{\binom{s_\mu}{\rightarrow}}{\mu^+} \longleftarrow \underset{s_\pi=0}{\pi^+} \longrightarrow \underset{\binom{s_\nu}{\leftarrow}}{\nu_\mu}$$

left-handed μ^+ left-handed ν_μ

$$\xrightarrow{\hat{\mathcal{C}}\hat{\mathcal{P}}}$$

$$\underset{\binom{s_{\overline{\nu}}}{\leftarrow}}{\overline{\nu}_\mu} \longleftarrow \underset{s_\pi=0}{\pi^-} \longrightarrow \underset{\binom{s_\mu}{\rightarrow}}{\mu^-}$$

right-handed $\overline{\nu}_\mu$ right-handed μ^-

$$\underset{\binom{s_\mu}{\leftarrow}}{\mu^-} \longleftarrow \underset{s_\pi=0}{\pi^-} \longrightarrow \underset{\binom{s_{\overline{\nu}}}{\rightarrow}}{\overline{\nu}_\mu}$$

right-handed μ^- right-handed $\overline{\nu}_\mu$

$$\xrightarrow{\hat{\mathcal{C}}\hat{\mathcal{P}}}$$

$$\underset{\binom{s_\nu}{\rightarrow}}{\nu_\mu} \longleftarrow \underset{s_\pi=0}{\pi^+} \longrightarrow \underset{\binom{s_\mu}{\leftarrow}}{\mu^+}$$

left-handed ν_μ left-handed μ^+

The world is back to normal under $(\hat{\mathcal{C}}\hat{\mathcal{P}})$.
Perhaps it is $(\mathcal{C}\mathcal{P})$ that is always conserved ?

Fundamental Discrete Symmetries

The fall of $(\mathcal{C}\mathcal{P})$ invariance[65]

Weak K-meson decays under $(\mathcal{C}\mathcal{P})$:

$$\begin{aligned}
(\hat{\mathcal{C}}\hat{\mathcal{P}})\,|K_1\rangle &= (\hat{\mathcal{C}}\hat{\mathcal{P}})\,\frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle - \left|\overline{K}^0\right\rangle\right) = +1\,|K_1\rangle \qquad \tau_1 \approx 10^{-10}[s] \\
(\hat{\mathcal{C}}\hat{\mathcal{P}})\,|K_2\rangle &= (\hat{\mathcal{C}}\hat{\mathcal{P}})\,\frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle + \left|\overline{K}^0\right\rangle\right) = -1\,|K_2\rangle \qquad \tau_2 \approx 5\times 10^{-8}[s] \\
(\hat{\mathcal{C}}\hat{\mathcal{P}})\,\left|\pi^+\pi^-\right\rangle &= (-1)^2\,\hat{\mathcal{C}}\,\left|\pi^+\pi^-\right\rangle = +1\,\left|\pi^+\pi^-\right\rangle \\
(\hat{\mathcal{C}}\hat{\mathcal{P}})\,\left|\pi^+\pi^-\pi^0\right\rangle &= (-1)^3\,\hat{\mathcal{C}}\,\left|\pi^+\pi^-\pi^0\right\rangle = -1\,\left|\pi^+\pi^-\pi^0\right\rangle
\end{aligned}$$

However, in 0.2% of decays: $|K_2\rangle \longrightarrow |\pi^+\pi^-\rangle \quad \Rightarrow (\hat{\mathcal{C}}\hat{\mathcal{P}})$-**nonconservation**

Therefore: $|K_L\rangle = \frac{1}{\sqrt{1+\varepsilon}}\left(|K_2\rangle + \varepsilon\,|K_1\rangle\right) \qquad \varepsilon \approx 2.3\times 10^{-3}$

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[65] J. H. Christenson et al., *Phys Rev Lett* **13** (1964) *138*

Fundamental Discrete Symmetries

$(\mathcal{C}\mathcal{P})$-Violation and Matter-Antimatter Asymmetry[66]

In 39% of events K_L decays differently:

$$K_L \longrightarrow \begin{cases} \pi^+ + e^- + \overline{\nu}_e & (-) \\ \pi^- + e^+ + \nu_e & (+) \end{cases}$$

N^+: decay into e^+
N^-: decay into e^-

$$\delta = \frac{N^+ - N^-}{N^+ + N^-} \approx 3 \times 10^{-3}$$

$(\hat{\mathcal{C}}\hat{\mathcal{P}})\,(\pm) \to (\mp)$

$|K_L\rangle$ is not $(\hat{\mathcal{C}}\hat{\mathcal{P}})$ eigenstate.

$(\hat{\mathcal{C}}\hat{\mathcal{P}})$-violation

$\Rightarrow N = N_e - N_{\overline{e}} \neq 0$

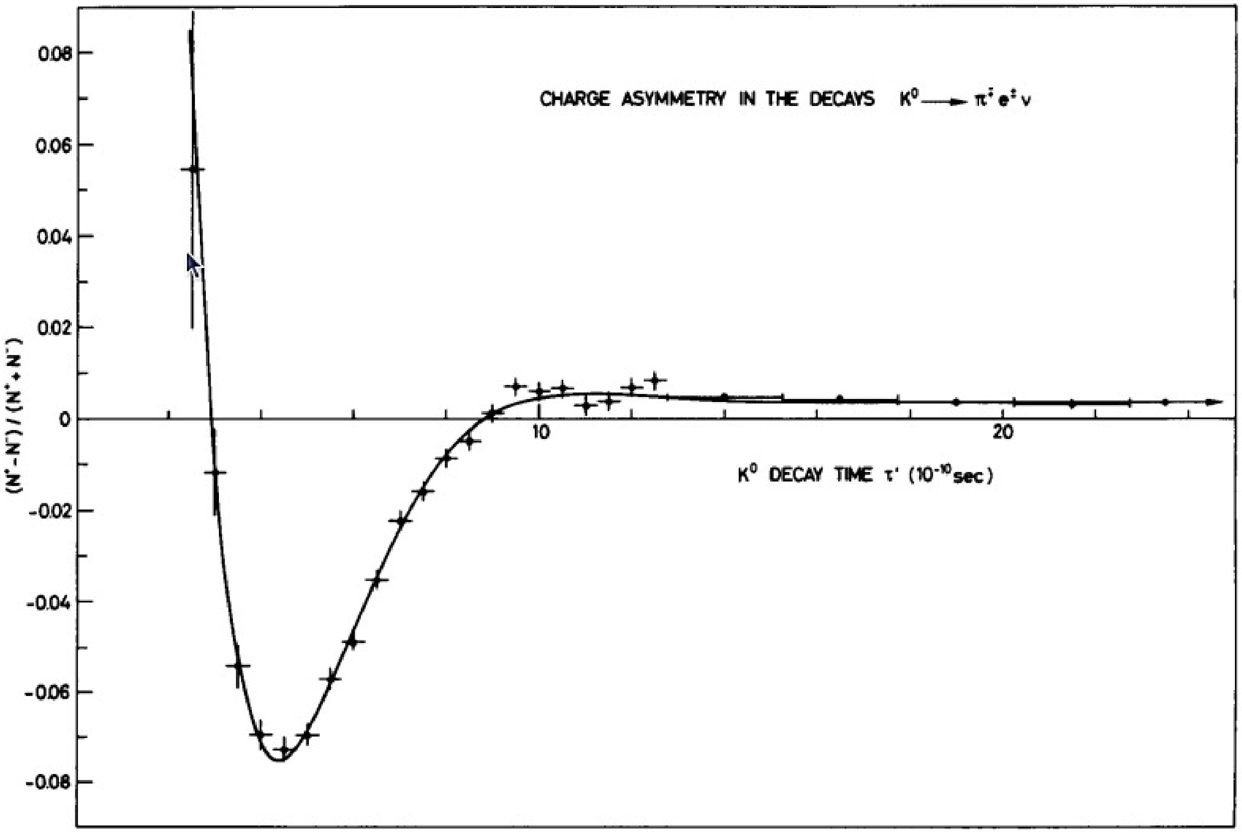

Fig. 1. The charge asymmetry as a function of the reconstructed decay time τ' for the K_{e3} decays. The experimental data are compared to the best fit as indicated by the solid line.

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[66] S. Gjesdal et al., *Phys Lett* **52B** (1974) *113*
F. Wilczek (1980)

Fundamental Discrete Symmetries

$(\mathcal{CP})$-Violation in the Standard Model[67]

CKM quark-generation mixing matrix for charged weak interactions among quarks:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} c_1 & s_1 c_3 & s_1 s_3 \\ -s_1 c_2 & c_1 c_2 c_3 - s_2 s_3\, e^{\imath\delta} & c_1 c_2 s_3 + s_2 c_3\, e^{\imath\delta} \\ -s_1 s_2 & c_1 s_2 c_3 + c_2 s_3\, e^{\imath\delta} & c_1 s_2 s_3 - c_2 c_3\, e^{\imath\delta} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

includes complex phase with $(\mathcal{CP})$-violating "δ parameter".

Cosmology:

A Matter-Antimatter Universe?[68] ⟶ ruled out.

Leptogenesis[69]

Electroweak baryogenesis[70]

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[67] C. Cabibbo, *Phys Rev Lett* **10** (1963) *531*
M. Kobayashi, K. Maskawa, *Prog Theor Phys* **49** (1973) *652*

[68] A.G. Cohen, A. De Rújula, S.L. Glashow, *Astrophys J* **495** (1998) *539*

[69] S. Davidson, E. Nardi, Y. Nir, *Phys Rep* **466** (2008) *105*

[70] D.E. Morrissey, M.J. Ramsey-Musolf, *New J Phys* **14** (2012) *125003*