EDMs as probes of multi-TV physics

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Pospelov, Ritz, Annals of Physics, 2005
[old review]

Plan

- **Intro: background on EDMs.**
- EDMs probing TeV scales.
- Review of EDMs in the SM, and new result for SM EDMs (θ_{QCD}, δ_{CKM})
- New constraints on EDMs of heavy particles, including a new constraint on muon EDM.

Purcell and Ramsey (1949) ("How do we know that strong interactions conserve parity?" $\longrightarrow |d_n| < 3 \times 10^{-18} e\mathrm{cm}$.)

MDM EDM

$$H = -\mu \mathbf{B} \cdot \frac{\mathbf{S}}{S} - d\mathbf{E} \cdot \frac{\mathbf{S}}{S}$$

$d \neq 0$ means that both P and T are broken. If CPT holds then CP is broken as well.

CPT is based on locality, Lorentz invariance and spin-statistics = very safe assumption.

search for EDM = search for CP violation, if CPT holds

Relativistic generalization

$$H_{\mathrm{T,P-odd}} = -d\mathbf{E} \cdot \frac{\mathbf{S}}{S} \to \mathcal{L}_{\mathrm{CP-odd}} = -d\frac{i}{2}\overline{\psi}\sigma^{\mu\nu}\gamma_5\psi F_{\mu\nu},$$

corresponds to dimension five effective operator and naively suggests $1/M_{\text{new physics}}$ scaling. Due to $SU(2) \times U(1)$ invariance, however, it scales as m_f/M^2.

Current limits translate to multi-TeV sensitivity to M.

Why bother with EDMs?

Is the accuracy sufficient to probe TeV scale and beyond?

Typical energy resoultion in modern EDM experiments

$$\Delta\text{Energy} \sim 10^{-6}\text{Hz} \sim 10^{-21}\text{eV}$$

translates to limits on EDMs

$$|d| < \frac{\Delta\text{Energy}}{\text{Electric field}} \sim 10^{-25}\text{e} \times \text{cm}$$

Comparing with theoretically inferred scaling,

$$d \sim 10^{-2} \times \frac{1 \text{ MeV}}{\Lambda_{CP}^2},$$

Large factor

we get **sensitivity to**

$$\Lambda_{CP} \sim 1 \text{ TeV}$$

Comparable with the LHC reach!

Current Experimental Limits

"paramagnetic EDM", Berkeley experiment

$|d_{\rm Tl}| < 9 \times 10^{-25} e\,{\rm cm}$ Interpreted $|d_e| < 1.6 \times 10^{-27}$

"diamagnetic EDM", U of Washington experiment

$|d_{\rm Hg}| < 2 \times 10^{-28} e\,{\rm cm}$

factor of 7 improvement in 2009! And another factor of 4 in 2016

$|d_{\rm Hg}| < 3 \times 10^{-29} e\,{\rm cm}$ $7.4 \times 10^{-30}\, e$ cm

neutron EDM, ILL experiment

$|d_n| < 3 \times 10^{-26} e\,{\rm cm}$ $1.8 \times 10^{-26}\, e$ cm

Notice that Thallium EDM is usually quoted as $d_e < 1.6\ 10^{-27}$ e cm
bound. It was modestly improved by YbF^+ results. **$|d_e| < 4.1 \times 10^{-30}$** **$|d_e| < 1.1 \times 10^{-29}$**

2013 ThO result by Harvard-Yale collaboration: $|d_e| < 8.7 \times 10^{-29}$

"Confirmed" using different techniques at JILA, $|d_e| < 1.3 \times 10^{-28}$

If dark matter particles have EDM...

it also must be small. They will contribute to the elastic scattering on normal nuclei (Pospelov, ter Veldhuis, 2000),

$$\sigma = 8\pi Z^2 \left(\frac{d}{e}\right)^2 \left(\frac{\alpha}{v}\right)^2 \frac{S+1}{3S} \ln \frac{q_{min}}{q_{max}}.$$

Recent constraints from Xenon 100 experiments would limit an EDM of a hypothetical 100 GeV WIMP to better than 10^{-23} e cm.

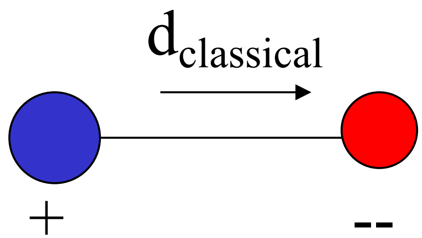
LZ experimental results [2022] limit e.g. EDM of a 30 GeV dark matter particle as $1*10^{-25}$ e cm.

Neutrino EDM: also cannot be large as otherwise it will provide too strong a source for the energy loss mechanism and/or too much of neutrino scattering.

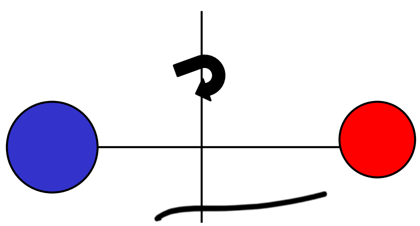
$d_\nu \sim \mu_\nu <$ few $*10^{-23}$ e cm.

A small comment on classical EDMs

- Fundamental EDMs are connected to spin, classical EDMs are not.
- A diatomic molecule (like ThO) will have a classical EDM.



- However, in a quantum state with fixed angular momentum classical EDM average to zero, exactly. States with +M and –M projection of angular momentum remain degenerate (at B=0).



$$< d_{classical} > = 0$$

- If there is fundamental CP-violation, the electric field will induce splitting between +M and –M states, e.g. Zeeman effect but with electric field. EDM experiments are looking for E coupling to spin

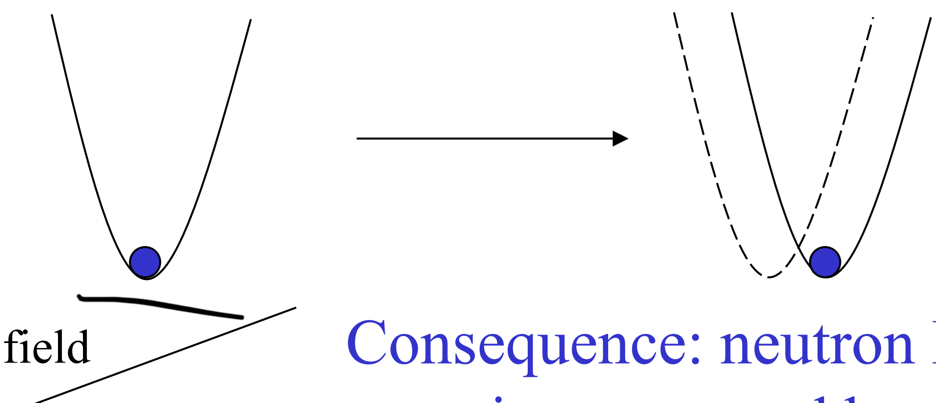
Importance of Schiff's screening

- Electric field experienced by the nucleus averages to 0 – (otherwise the atom would accelerate).

$$\Delta E = -d\langle i|(\mathcal{E}\cdot s_n)|i\rangle - \sum_{k\neq i}\frac{\langle i|(\mathcal{E}\cdot er_e)|k\rangle\langle k|(d/e)s_n\cdot\nabla_{r_n}U(r_n-r_e)|i\rangle}{E_i-E_k} - \sum_{k\neq i}\frac{\langle i|(d/e)s_n\cdot\nabla_{r_n}U(r_n-r_e)|k\rangle\langle k|(\mathcal{E}\cdot er_e)|i\rangle}{E_i-E_k}$$

$$= -d\langle i|(\mathcal{E}\cdot s_n)|i\rangle - d\sum\frac{\langle i|(\mathcal{E}\cdot r_e)|k\rangle\langle k|[(s_n\cdot ip_e),H]|i\rangle + \langle i|[(s_n\cdot ip_e),H]|k\rangle\langle k|(\mathcal{E}\cdot r_e)|i\rangle}{E_i-E_k}$$

$$= -d\langle i|(\mathcal{E}\cdot s_n)|i\rangle - d\langle i|[(\mathcal{E}\cdot r_e),(s_n\cdot ip_e)]|i\rangle = -d\langle i|(\mathcal{E}\cdot s_n)|i\rangle + d\langle i|(\mathcal{E}\cdot s_n)|i\rangle = 0$$



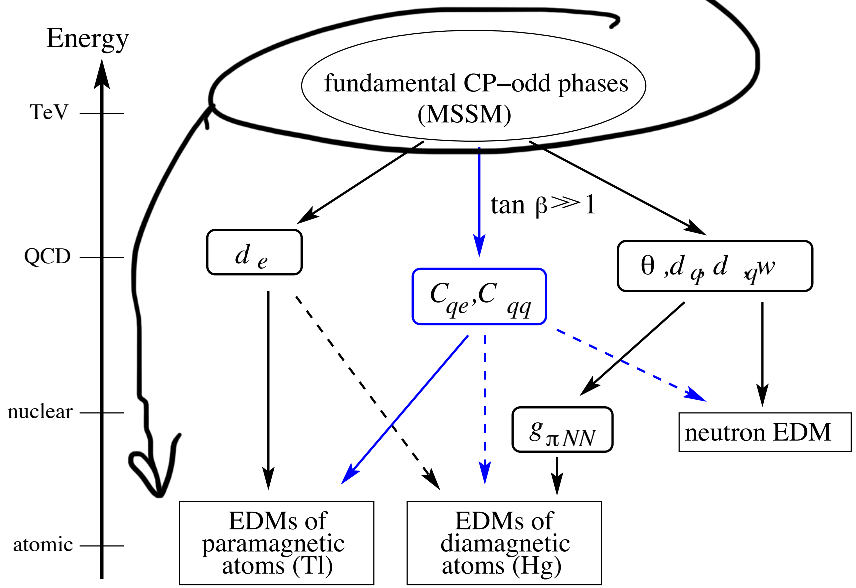
External E field

A nonrelativistic point-like charged particle has an equilibrium position at a point where E =0

Consequence: neutron EDM inside e.g. ^{3}He atom is suppressed by $(R_{nucl}/a_{atom})^2$

BSM physics and EDMs

$$\mathcal{L}_{eff}^{1\text{GeV}} = \frac{g_s^2}{32\pi^2}\,\theta_{QCD}\, G^a_{\mu\nu}\widetilde{G}^{\mu\nu,a}$$
$$-\frac{i}{2}\sum_{i=e,u,d,s} d_i\, \overline{\psi}_i (F\sigma)\gamma_5\psi_i - \frac{i}{2}\sum_{i=u,d,s}\widetilde{d}_i\, \overline{\psi}_i g_s (G\sigma)\gamma_5\psi_i$$
$$+\frac{1}{3} w\; f^{abc} G^a_{\mu\nu}\widetilde{G}^{\nu\beta,b} G_{\beta}{}^{\mu,c} + \sum_{i,j=e,d,s,b} C_{ij}\; (\bar{\psi}_i\psi_i)(\bar{\psi}_j i\gamma_5\psi_j) + \cdots$$



- One needs hadronic, nuclear, atomic matrix elements to connect Wilson coefficients to observables

- Extremely high scales [10-100 TeV] can be probed if new physics generating EDMs violates CP maximally.

Neutron/proton EDM status

- Continuing efforts to improve d_n at PSI, Los Alamos, SNS, TRIUMF. Need [a lot] more ultra-cold neutrons to improve sensitivity. Hard to achieve as intense UCN sources are technologically challenging.
- Calculations are of secondary importance. Lattice have solid results for $d_n(d_{u,d})$ but struggles with theta term, color EDMs of quarks and Weinberg operator. We have to rely on old QCD SR estimates (MP and Ritz), and/or chiral PT.
- Proton EDM (so far constrained indirectly) in the storage ring – interesting proposal, and it is easy to believe that statistics can be advantageous over neutrons, but the whole new technology of non-magnetic storage rings has to be developed.

Diamagentic EDMs, status

- ^{199}Hg EDM experiment has last result in 2016. Sensitivity to fundamental CP violation is reduced by the Schiff screening of nuclear EDM. Intermediate observable is the Schiff moment, that parametrizes the difference between charge and EDM distribution inside the nucleus, $[S/e] = \mathrm{fm}^3$. Limit on S translates to an indirect limit on d_n similar to a direct one. Penalty: $(Z\alpha m_e R_N)^2 \sim 10^{-4}$.

- $d_{Atom}(S(g_{\pi nn}(\theta, CEDM)))$ requires QCD, nuclear and atomic impact. Atomic theory is under control, *some* QCD calculations are simple, but $S(g_{\pi nn})$ had some difficulties. Recent shell model answers are more in line with older studies. Equivalent constraint on triplet color EDM is at $\sim 10^{-27}$ e cm. Very competitive.

- Future hopes are linked to large enhancement of S due to octupole deformations of some nuclei (e.g. ^{225}Ra).

Progress in paramagentic EDMs

$|d_e| < 1.6 \times 10^{-27}$e cm → $|d_e| < 4.1 \times 10^{-30}$ e cm (HfF+), 1.1×10^{-29}(ThO)

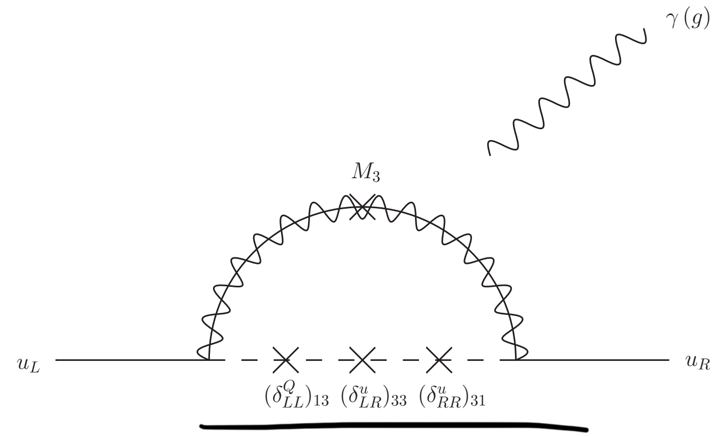
- In the last ~ 10 years, improved by a factor of ~ 400.
- Sensitivity is usually quoted as d_e. Relativistically enhanced as $d_{Atom} \sim Z^3 \alpha^2 d_e$. In reality, d_{Atom} is a linear combination of d_e and a semileptonic operator. Using most sensitive results from ThO and HfF+ molecules, one can limit both sources. Diatomic molecules have strong internal field and can effectively "enhance" modest external E field.
- More progress is real (e.g. ACME III). Some other daring proposals want to go down to $d_e \sim 10^{-34}$ e cm.
- Theoretically is the cleanest. Atomic theory is under control at ~ 10% accuracy. In many models - minimum of QCD/nuclear input. SM contributions (θ_{QCD} and δ_{CKM}) were calculated in the last three years. Benchmark CKM value $d_e^{eq} = 1.0 * 10^{-35}$ e cm.

BSM: SUSY at 100 TeV and EDMs

(EDMs are not hopeless)

$$d_f \sim c_1 \frac{\delta m_f}{\Lambda^2_{\rm SUSY}} \theta_{\rm CP},$$

$$\tilde{d}_q \sim c_2 \frac{\delta m_q}{\Lambda^2_{\rm SUSY}} \ln\left(\frac{M_3^2}{\Lambda^2_{\rm SUSY}}\right) \theta_{\rm CP}$$



- Higgs mass point to a large scale of SUSY breaking, 10-100 TeV
- The requirements on approximately "flavor-aligned" scalar quark and scalar lepton sector are softened.
- LR mixing of quarks and leptons can get ~ m_t and m_τ instead of m_u and m_e. This can lead to a significant enhancement (McKeen, MP, Ritz, 2013)

$$\tilde{d}_u \simeq 5\times 10^{-26}\,{\rm cm} \left(\frac{4}{\tan\beta}\right)\left(\frac{\theta^2_{u13} M_3}{300\,{\rm GeV}}\right)\left(\frac{100\,{\rm TeV}}{\Lambda_{\rm SUSY}}\right)^3 \times \left[\ln\left(\frac{\Lambda^2_{\rm SUSY}}{M_3^2}\right)/10\right]\left(\frac{\sin\phi_{\tilde{u}\mu}}{1/\sqrt{2}}\right).$$

$$d_e \sim e f_e(r_1) \frac{\delta m_e}{\Lambda^2_{\rm SUSY}} \sin\phi_{\tilde{e}\mu}$$

$$\simeq 1\times 10^{-29}\, e\,{\rm cm} \left(\frac{\tan\beta}{4}\right)\left(\frac{\theta^2_{e13} M_1}{300\,{\rm GeV}}\right) \times \left(\frac{100\,\,{\rm TeV}}{\Lambda_{\rm SUSY}}\right)^3 \left(\frac{\sin\phi_{\tilde{e}\mu}}{1/\sqrt{2}}\right),$$

Application to Higgs physics: CP-odd channel for Higgs-γ–γ coupling

Consider two effective operators from some physics that is integrated out:

$$\frac{c_h v}{\Lambda^2}\underbrace{hF_{\mu\nu}F^{\mu\nu}} + \frac{\tilde{c}_h v}{\tilde{\Lambda}^2}\underbrace{hF_{\mu\nu}\tilde{F}^{\mu\nu}}$$

Then, $\underline{R_{\gamma\gamma}} = \dfrac{\Gamma_{\gamma\gamma}}{\Gamma^{\rm SM}_{\gamma\gamma}} \simeq \left|1 - c_h \dfrac{v^2}{\Lambda^2}\dfrac{8\pi}{\alpha A_{\rm SM}}\right|^2 + \left|\tilde{c}_h \dfrac{v^2}{\tilde{\Lambda}^2}\dfrac{8\pi}{\alpha A_{\rm SM}}\right|^2$

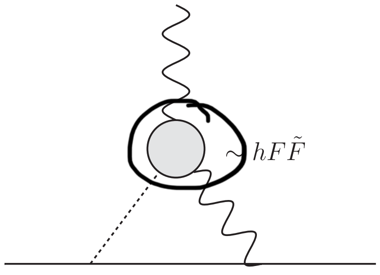
and deviations are O(1) if $c/\Lambda \sim 1/5$ TeV.

Given that coefficients c and $\tilde{c}$ are most likely perturbative, $\sim \alpha$, then O(1) deviations are only if Lambda is relatively low.

Higgs-gamma loop induces electron EDM

Integrating *h-gamma*, we end up with log-sensitivity to UV scale,

$$d_i = \tilde{c}_h \frac{|e| m_f}{4\pi^2 \tilde{\Lambda}^2} \ln\left(\frac{\Lambda^2_{\rm UV}}{m_h^2}\right)$$
$$= d_f^{(2l)} \times \frac{\tilde{c}_h}{\alpha/(4\pi)} \times \frac{v^2}{\tilde{\Lambda}^2} \ln\left(\frac{\Lambda^2_{\rm UV}}{m_h^2}\right)$$



Assuming h couples to e

Cutting the log at the same scale, one ends up with

$$\tilde{\Lambda} \gtrsim 50\sqrt{\tilde{c}_h}\,\mathrm{TeV}.$$

which is a lot *larger* than h→2 gamma rates "wants".
Consequently, once the EDM bound is imposed,

$$\Delta R_{\gamma\gamma}(\tilde{c}_h) \lesssim 1.6 \times 10^{-4}.$$

New number: $\Delta R_{\gamma\gamma} < 1.1\times10^{-6}$

This is very restrictive.

Conclusion: unless one fine-tunes EDMs to 0, Higgs→ $\gamma\gamma$ amplitude cannot have a large CP-odd admixture.

Two sources of CP-violation in SM

- Theta term of QCD: *too large EDMs if theta is arbitrary* → new naturalness problem because of EDMs. ($d_n \sim \theta m_q/m_n^2$, $\theta < 10^{-10}$)

- Cabibbo-Kobayashi-Maskawa matrix and nearly maximal CP phase → still EDMs are *too small to be observable* in the next round of EDM experiments.

- Importantly, both SM sources are too small for efficient generation of the baryon-antibaryon asymmetry. Requires BSM!

Strong CP problem

Energy of QCD vacuum depends on θ-angle:

$$E(\bar{\theta}) = -\frac{1}{2}\bar{\theta}^2 m_* \langle \overline{q} q \rangle + \mathcal{O}(\bar{\theta}^4, m_*^2)$$

where $\langle \overline{q} q \rangle$ is the quark vacuum condensate and m_* is the reduced quark mass, $m_* = \frac{m_u m_d}{m_u + m_d}$. In CP-odd channel,

$$d_n \sim e \frac{\bar{\theta} m_*}{\Lambda_{\rm had}^2} \sim \bar{\theta} \cdot (6 \times 10^{-17})\, e\, \mathrm{cm}$$

Strong CP problem = naturalness problem = Why $|\bar{\theta}| < 10^{-9}$ when it could have been $\bar{\theta} \sim O(1)$? $\bar{\theta}$ can keep "memory" of CP violation at Planck scale and beyond. Suggested solutions

- Minimal solution $m_u = 0 \leftarrow$ apparently can be ruled out by the chiral theory analysis of other hadronic (CP-even) observables.
- $\bar{\theta} = 0$ by construction, requiring either exact P or CP at high energies + their spontaneous breaking. Tightly constrained scenario.
- Axion, $\bar{\theta} \equiv a(x)/f_a$, relaxes to $E = 0$, eliminating theta term. $a(x)$ is a very light field. Not found so far.

EDMs induced by θ_{QCD}

- Neutron EDM.

$$d_n \simeq e \times g_A \times (15 \times 10^{-3}\theta)\frac{\log(m_N^2/m_\pi^2)}{8\pi^2 F_\pi},$$

Crewther et al showed logarithmic sensitivity to m_π, and numerically this is ~ few 10^{-16} e cm. $\Theta < 10^{-10}$. One can also use QCD sum rules to estimate d_n (MP and Ritz)

$$d_n^{\rm est} = \frac{8\pi^2|\langle\overline{q}q\rangle|}{m_n^3}\left[-\frac{2\chi m_*}{3}e(\bar\theta - \theta_{\rm ind}) + \frac{1}{3}(4d_d - d_u) + \frac{\chi m_0^2}{6}(4e_d\tilde{d}_d - e_u\tilde{d}_u)\right],$$

- ^{199}Hg EDM. This is the tightest constraint on atomic EDM, the sensitivity to theta is reduced because one has to use Schiff moment of the nucleus. Similar sensitivity to θ, with different systematics.
- Paramagnetic EDMs (aka electron EDM) – coupling of electric field to an unpaired electron spin. *What is the sensitivity to theta?*

CP violation via in CKM matrix

There are two possible sources of CP violation at a renormalizable level: δ_{KM} and θ_{QCD}.

δ_{KM} is the form of CP violation that appears only in the charged current interactions of quarks.

$$\mathcal{L}_{cc} = \frac{g}{\sqrt{2}}\left(\bar{U}_L \not{W}^+ V D_L + (\mathrm{H.c.})\right).$$

CP violation is closely related to flavour changing interactions.

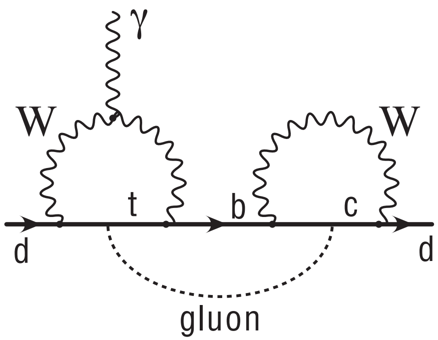
$$\begin{pmatrix} d^I \\ s^I \\ b^I \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \equiv V_{\mathrm{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}.$$

CKM model of CP violation is independenly checked using nutral K and B systems. *No other sources of CP are needed to describe observables!*

CP violation disappear if any pair of the same charge quarks is degenerate or some mxing angles vanish.

$$J_{CP} = \mathrm{Im}(V_{tb}V_{td}^* V_{cd} V_{cb}^*) \times$$
$$(y_t^2 - y_c^2)(y_t^2 - y_u^2)(y_c^2 - y_u^2)(y_b^2 - y_s^2)(y_b^2 - y_d^2)(y_s^2 - y_d^2)$$
$$< 10^{-15}$$

EDMs from SM sources: CKM



CKM phase generates tiny EDMs:

$$d_d \sim \mathrm{Im}(V_{tb}V_{td}^* V_{cd}V_{cb}^*)\alpha_s m_d G_F^2 m_c^2 \times \text{loop suppression}$$

$$< 10^{-33} e\mathrm{cm}$$

- Quark EDMs identically vanish at 1 and 2 loop levels, $EW^2=0$

(Shabalin, 1981).

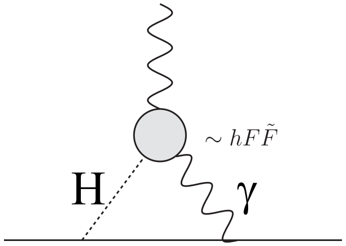
- 3-loop EDMs, EW^2QCD^1 are calculated by Khriplovich; Czarnecki, Krause.

- d_e vanishes at EW^3 level (Khriplovich, MP, 1991) < 10^{-38} e cm. It was calculated recently by Yamaguchi, Yamanaka to be 6 10^{-40} e cm

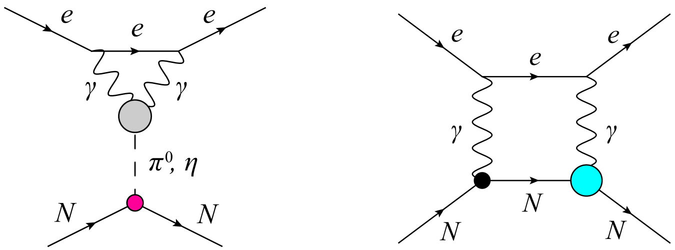
- Long distance effects give neutron EDM ~ 10^{-32} e cm; *uncertain*.

Recent results: Hadronic CP violation → paramagnetic EDMs

- CP violation in top-Higgs sector – Barr Zee diagrams, h-γ mediation

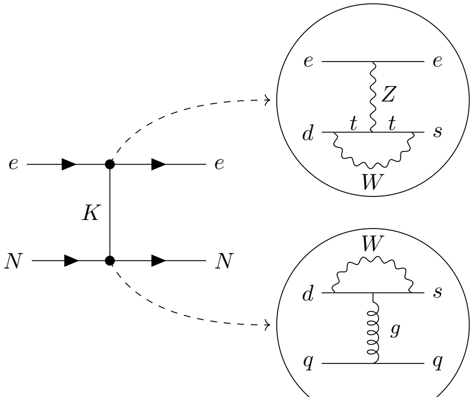


- Theta term, light quark, mu EDMs -- γ–γ mediation



$C_S(\theta)$

- Kobayashi-Maskawa CP-violation – Z (and WW) mediation



$C_S(\delta_{CKM})$

"Paramagnetic" EDMs:

- Paramagnetic EDM (EDM carried by electron spin) can be induced not only by a purely leptonic operator

$$d_e \times \frac{-i}{2}\,\overline{\psi}\sigma_{\mu\nu}\gamma_5 F_{\mu\nu}\psi$$

but by semileptonic operators as well:

$$H \sim C_S \times \frac{G_F}{\sqrt{2}m_e} \times (\mathbf{S}_e\nabla)\delta(\mathbf{r}_e)$$

$$C_S \times \frac{G_F}{\sqrt{2}}\,\overline{N}N\,\overline{\psi}i\gamma_5\psi$$

- Only a linear combination is limited in any single experiment. ThO 2018 ACME result is:

$|d_e| < 1.1\times10^{-29}$ e cm at $C_S = 0$

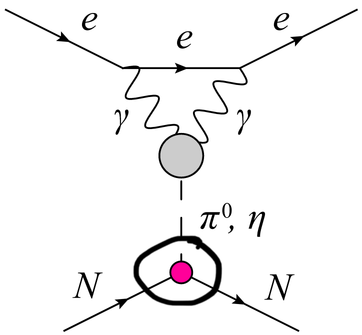
$|C_S^{\text{singlet}}| < 7.3\times10^{-10}$ at $d_e = 0$

$$d_e^{\text{equiv}} = d_e + C_S \times 1.5 \times 10^{-20}\,e\,\text{cm}$$ ← Specific for ThO

$$d_e^{equiv} = d_e + C_S{*}0.9{*}10^{-20}\,e\,cm$$ ← Specific for Hf F+

LO chiral contribution:

- T-channel pion exchange gives



$$\mathcal{L} = \theta \times \frac{1}{m_\pi^2} \times 0.017 \times 3.5 \times 10^{-7} (\bar{e} i \gamma_5 e)(\bar{n} n - \bar{p} p)$$

$$= (\bar{e} i \gamma_5 e)(\bar{n} n - \bar{p} p) \times \frac{3.2 \times 10^{-13} \theta}{\mathrm{MeV}^2}.$$

implying $|\theta| < 8.4 \times 10^{-8}$ sensitivity. However, adding exchange of η_8,

$$1 \to 1 - \frac{1}{3} \frac{f_\pi^2 m_\pi^2}{f_\eta^2 m_\eta^2} \times \frac{m_d - m_u}{m_d + m_u} \times \frac{A \times \sigma_N}{\frac{m_d - m_u}{2} \langle p | \bar{u} u - \bar{d} d | p \rangle \times (N - Z)}$$

$$1 \to 1 - 0.88 \simeq 0.12.$$

The effect can completely cancel within error bars on nucleon sigma term σ_N.

Photon box diagrams:

- Diagrams are IR divergent but regularized by Fermi momentum in the Fermi gas picture of a nucleus (intermediate N is above Fermi surface).

$$\mathcal{L} = \bar{e} i\gamma_5 e \bar{N} N \times \frac{2m_e \times 4\alpha \times \overline{d\mu} \times 6.2}{\pi p_F} = \bar{e} i\gamma_5 e \bar{N} N \times 2.4 \times 10^{-4} \times \overline{d\mu}$$

$$\overline{d\mu} = \frac{Z}{A}\mu_p d_p + \frac{A-Z}{A}\mu_n d_n = \frac{e}{2m_p} \times (1.08 d_p - 1.16 d_n)$$

- Nucleon EDM (theta) is very much a triplet, $d_p \simeq -d_n \simeq 1.6 \times 10^{-3} e\mathrm{fm}\theta$

Full answer including chiral NLO. (accidental cancellation of π^0 and η)

$$\boxed{C_{SP}(\bar{\theta}) \approx \left[0.1_{\mathrm{LO}} + 1.0_{\mathrm{NLO}} + 1.7_{(\mu d)}\right] \times 10^{-2}\bar{\theta} \approx 0.03\,\bar{\theta}}$$

Limit on theta term from ThO (electron EDM) experiment:

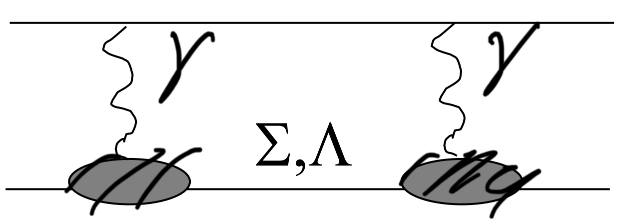
$$\boxed{|\bar{\theta}|_{\mathrm{ThO}} \lesssim 3 \times 10^{-8}}$$

Flambaum, MP, Ritz, Stadnik, 2020

* Improved by a factor of ~ 2 in Dec 2022, $\theta < 1.5 * 10^{-8}$

CKM CP-violation and paramagnetic EDMs

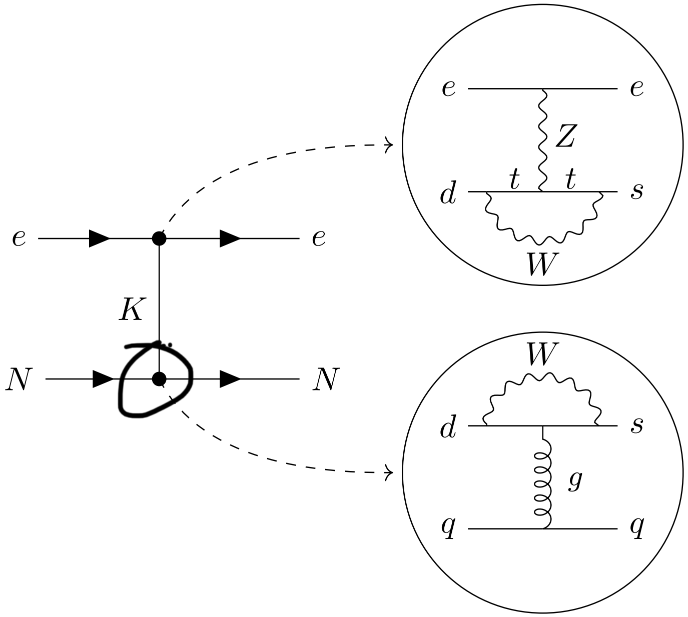
- Several groups attempted to calculate d_e (MP, Khriplovich; …)
- The result is small to the point of being not interesting (e.g. 10 orders of magnitude below current bounds)
- Semileptonic (C_S) operator is more important. MP and Ritz (2012) estimated two-photon mediated EW^2EM^2 effects and found that CS is induced at the level equivalent to ~ 10^{-38} e cm



ΔS = +/- 1   ΔS = -/+ 1

It turns out that there are much larger contributions at EW^3 order

Semileptonic CP operator at EW^3 order



- The induced semileptonic operator is calculable in chiral perturbation theory (in m_s expansion)
- The result is large, d_e(equiv) = + 1.0 10^{-35} e cm
- Same EW penguin that is responsible for $B_s \rightarrow \mu^+\mu^-$, Re $K_L \rightarrow \mu^+\mu^-$

Ema, Gao, MP, PRL2022

Final result

- Combining $(m_s)^{-1}$ and $(m_s)^{-1/2}$ effects, we get

$$\boxed{\begin{aligned} &C_S(\mathrm{LO}+\mathrm{NLO}) \simeq \underline{6.9\times 10^{-16}} \\ \Longrightarrow\ \ &d_e^{\mathrm{equiv}} \simeq \underline{1.0\times 10^{-35}\, e\,\mathrm{cm}.} \end{aligned}}$$

- The result EW^3 much larger than the EW^{2}EM^2 estimate by ~1000.

- Note that actually establishing the correct sign is tricky.

- The result is under "best possible" theoretical control, and can be improved on the lattice

$$\begin{aligned} &\langle N|i(\bar{s}\gamma_\mu(1-\gamma_5)d-\bar{d}\gamma_\mu(1-\gamma_5)s)|N\rangle_{\mathrm{EW}^1} \\ &\quad = \frac{f_S}{m_N} iq_\mu \bar{N}N + \frac{f_T}{m_N} q_\nu \bar{N}\sigma_{\mu\nu}\gamma_5 N. \end{aligned}$$

EDMs of heavy flavors

- Among Wilson coefficients of different kind, EDMs of heavy flavours d_i are interesting. $i =$ muon, tau, charm, bottom, top.

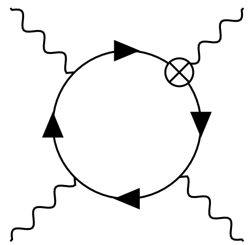
- Muon EDM is limited as a biproduct of BNL g-2 experiment. Can be significantly improved in dedicated beam experiments (PSI, Fermilab, J-Parc)

- There is a creative proposal to measure MDMs and limit EDMs of charmed baryons using thin fixed target and bent crystal technology just before the LHCb experiment (E. Bagli et al, 2017).

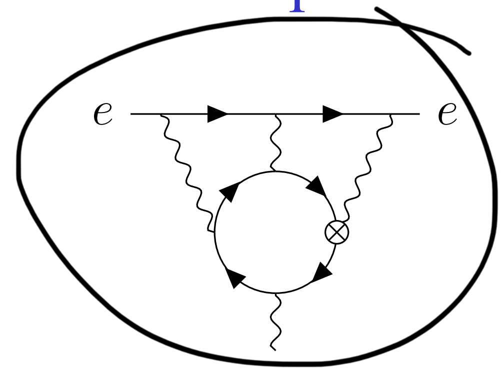
- Heavy flavors contribute to observable EDMs via loops. Top quark EDM is limited indirectly by electron EDM via a two-loop (top-Higgs-gamma) Barr-Zee diagrams. The result is stronger than the direct measurements at LHC.

Muon EDM inside a loop

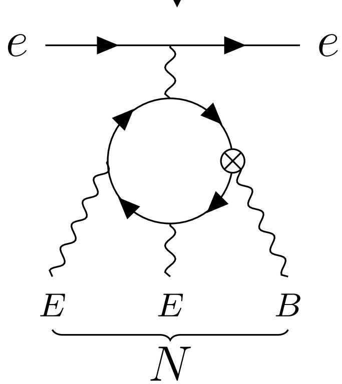
- Muon loop induces E^3B effects, and electron EDM at 3-loops.



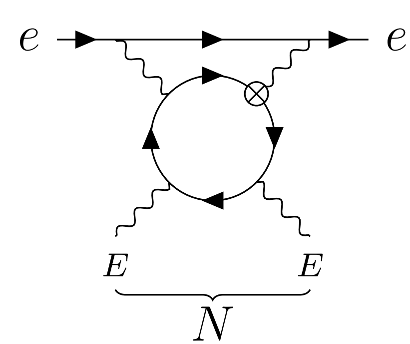
$$\mathcal{L} = -e^4(\tilde{F}_{\alpha\beta}F^{\alpha\beta})(F_{\gamma\delta}F^{\gamma\delta}) \times \frac{d_\mu/e}{96\pi^2 m_\mu^3}$$
$$= -\frac{d_\mu/e}{12\pi^2 m_\mu^3} e^4(\mathbf{E}\cdot\mathbf{B})(\mathbf{E}\cdot\mathbf{E}-\mathbf{B}\cdot\mathbf{B}),$$



Nuclear Schiff moment



Effective C_S operator



d_{Hg}

d_e^{equiv}(ThO)

New indirect constraints on muon EDM

- Owing to the fact that the electric field inside a large nucleus is not that small $eE \sim Z\alpha R_N^{-1} \sim 30$ MeV compared to m_μ, effects formally suppressed by higher power of m_μ win over three-loop electron EDM.

- New results:

Hg EDM experiment: $S_{^{199}\mathrm{Hg}}/e \simeq (d_\mu/e) \times 4.9 \times 10^{-7}\,\mathrm{fm}^2, \quad |d_\mu| < 6.4 \times 10^{-20}\, e\,\mathrm{cm}$

ThO EDM experiment: $d_e^{\mathrm{equiv}} \simeq 5.8 \times 10^{-10}\, d_\mu \implies \boxed{|d_\mu| < 1.9 \times 10^{-20}\, e\,\mathrm{cm}.}$

New limit from Boulder HfF: ~9*10^-21

- Factor of 20 improvement over the BNL constraint, $|d_\mu| < 1.8 \times 10^{-19}$
- New benchmark for the muon beam EDM experiments.

NB: 3-loop contributions calculated by Grozin et al. has been revised

- Tau EDM is constrained by three-loop induced d_e.

New indirect constraints on c-, b- quarks EDMs

- New results:

Neutron EDM experiment: $|d_c| < 6 \times 10^{-22}\, e\,\mathrm{cm}, \quad |d_b| < 2 \times 10^{-20}\, e\,\mathrm{cm},$

ThO EDM experiment: $|d_c| < 1.3 \times 10^{-20}\, e\,\mathrm{cm}, \quad |d_b| < 7.6 \times 10^{-19}\, e\,\mathrm{cm},$

- Neutron EDM estimates have uncertainty ~ up to a factor of O(few) due to limitation of QCD sum rule method in this channel. C_S derived limits have *minimal* uncertainty, O(10%).
- Independent of (similar order of magnitude) bounds based on RG running of operators, and contribution to the GGGdual Weinberg operator.
- The strength of these limits on charm EDM points to the conclusion that future charmed baryon EM moment proposal should focus on MDM.

Conclusions

- **Searches for EDMs are very important part of the fundamental physics program. Sensitive to ~ 100 TeV scales of New Physics.**
- In *lots of hadronic CP violation models*, including the SM, the paramagnetic EDMs (*experiments looking for d_e*) are induced by the semi-leptonic operators of (electron pseudoscalar)*(nucleon scalar) type.
- C_S is induced by theta term via a two-photon exchange resulting in sensitivity $|\theta| < 1.5\times10^{-8}$. Further progress by O(100) for d_e type of experiments will bring the sensitivity to hadronic CP violation on par with current d_n limits.
- CKM CP violation induces C_S. The result is large and calculable and is dominated by the EW^3 order. The *equivalent* d_e (ThO) is found to be $+1.0 \times 10^{-35}$ e cm. This is 1000 times larger than previously believed.
- New indirect limits on muon, charm and bottom provide new target for the EDM beam experiments: $d_\mu < 9 \times 10^{-21}$ e cm

Semileptonic Electroweak Penguin

- The upper part: EW penguin $\mathcal{L}_{\mathrm{EWP}} = \mathcal{P}_{\mathrm{EW}} \times \bar{e}\gamma_\mu\gamma_5 e \times \bar{s}\gamma^\mu(1-\gamma_5)d + (h.c.)$

$$\mathcal{L}_{Uee} = -\frac{if_0^2}{2}\mathcal{P}_{\mathrm{EW}} \times \bar{e}\gamma_\mu\gamma_5 e \times \mathrm{Tr}\left[h^\dagger\left(\partial^\mu U\right)U^\dagger\right] + (h.c.),$$

In the leading order, the dominant diagram is K_S exchange.

$$\mathcal{L}_{Kee} = -2\sqrt{2}f_0 m_e \bar{e}i\gamma_5 e\left(K_S \times \mathrm{Im}\mathcal{P}_{\mathrm{EW}} + K_L \times \mathrm{Re}\mathcal{P}_{\mathrm{EW}}\right)$$

- Lower part: EW[1] B-B-M coupling is related by flavor SU(3) to the s-wave amplitudes of the non-leptonic hyperon decays. Theory fit to decay amplitudes is [surprisingly] good (~5-10%):

$$\mathcal{L}_{\mathrm{SP}} = -a\mathrm{Tr}(\bar{B}\{\xi^\dagger h\xi, B\}) - b\mathrm{Tr}(\bar{B}[\xi^\dagger h\xi, B]) + (h.c.).$$

contains $2^{1/2}f_0^{-1}((b-a)\bar{p}p + 2b\bar{n}n)K_S$

LO kaon exchange result

- Using EW penguin and strong penguin below,

$$\mathcal{L}_{KNN} \simeq -\frac{\sqrt{2}\,G_F \times [m_{\pi^+}]^2 f_\pi}{|V_{ud}V_{us}| f_0} \times 2.84(0.7\bar{p}p + \bar{n}n)$$
$$\times \left(\mathrm{Re}(V_{ud}^* V_{us}) K_S + \mathrm{Im}(V_{ud}^* V_{us}) K_L\right).$$

We calculate C_S

$$C_S \simeq \mathcal{J} \times \frac{N + 0.7Z}{A} \times \frac{13[m_{\pi^+}]^2 f_\pi m_e G_F}{m_K^2} \times \frac{\alpha_{\mathrm{EM}} I(x_t)}{\pi \sin\theta_W^2}$$

$$\mathcal{J} = \mathrm{Im}(V_{ts}^* V_{td} V_{ud}^* V_{us}) \simeq 3.1 \times 10^{-5}$$

That has the following LO scaling

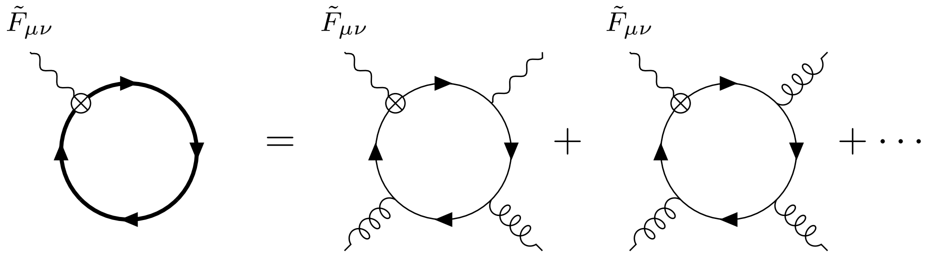
$$G_F C_S \propto \mathcal{J} G_F^3 m_t^2 m_e m_s^{-1} \Lambda_{\mathrm{hadr}}^2$$

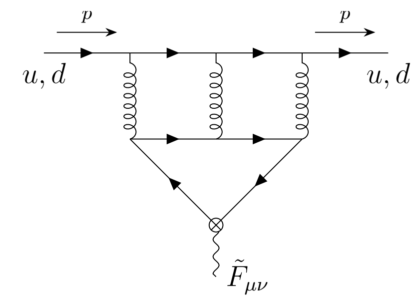
Numerically, it is

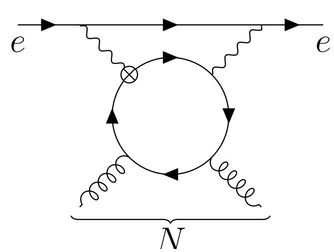
$$C_S(\mathrm{LO}) \simeq 5 \times 10^{-16}.$$

Charm and bottom EDMs

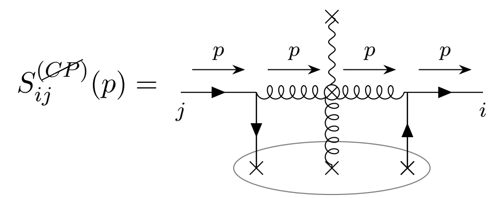
Charm loop gives $(\gamma)^2(\text{gluon})^2$ and $(\gamma)^1(\text{gluon})^3$ effective operators







$$\langle N|\frac{g_s^2}{32\pi^2}G^a_{\mu\nu}G^{a\mu\nu}|N\rangle = -\frac{m_N}{9}\bar{N}N,$$



Nonperturbative 3-gluon induced tensor charge

$d_e^{\text{equiv}}(\text{ThO})$

d_n , d_{Hg}

- All EDMs are induced by charm and bottom EDMs.