

The electron EDM and EDMs in Two-Higgs-Doublet Models

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Seminar at IFIC, Valencia
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Based on:

“A robust limit for the EDM of the electron”, MJ, JHEP 1305 (2013) 168,
“EDMs in Two-Higgs-Doublet Models”, MJ/Pich, JHEP 14xx (2014) xxx.

Outline

Introduction

A robust limit on the electron EDM

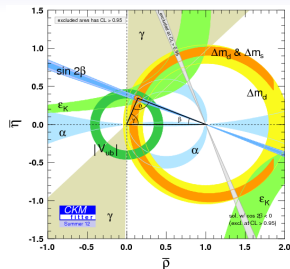
EDMs in 2HDMs

Conclusions and Outlook

Motivation

Flavour and CP violation in the SM:

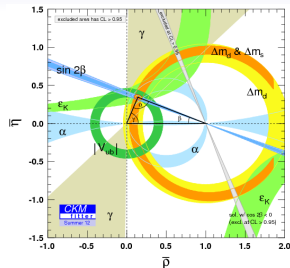
- CKM describes flavour **and** CP violation
- Extremely constraining, one phase
- Especially, K and B physics agree
- ➡ Works well!



Motivation

Flavour and CP violation in the SM:

- CKM describes flavour **and** CP violation
- Extremely constraining, one phase
- Especially, K and B physics agree
- ➡ Works **too** well!



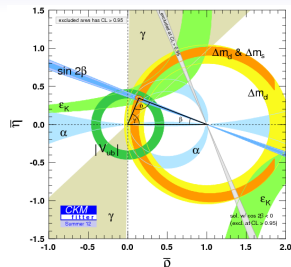
We expect new physics (ideally at the (few-)TeV scale):

- Baryon asymmetry of the universe
- Hierarchy problem
- Dark matter and energy
- ...

Motivation

Flavour and CP violation in the SM:

- CKM describes flavour **and** CP violation
- Extremely constraining, one phase
- Especially, K and B physics agree
- ➡ Works **too** well!



We expect new physics (ideally at the (few-)TeV scale):

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➡ So where is it?

The Quest for New Physics

We are living in interesting times! (Remember the curse?)

Three of the main paths to NP (also ν , astrophysics, ...):

- Tevatron results, LHC is running
 - Fantastic first three years at LHC
 - In layman's terms: **We've got it!**
 - New results just in the last two weeks
- Flavour machines
 - B factories (!), LHCb, ...
 - Lots to come!
Belle II, BES III, NA62, ...
- EDM experiments, $g - 2$, ...
 - Qualitative progress in EDMs, new mechanisms and methods
 - Most recent results: ThO molecules
 - Many experiments ongoing/planned

Direct search

**Indirect search,
flavour violating**

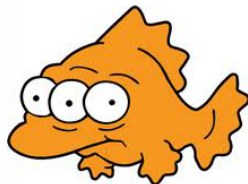
**Indirect search,
flavour conserving**

➡ Interplay important

The Quest for New Physics

Flavour-sector of the SM is special ($\rightarrow$):

- Unique connection between Flavour- and CP-violation
- FCNCs highly suppressed
- F~~C~~onservingNCs with CPV as well!



➡ $d_e^{SM} \lesssim 10^{-38} \text{ e cm}$ [Khriplovich/Pospelov '91]
Well below foreseeable tests!

EDMs extremely sensitive tests for new sources of CPV:

- Experimentally e.g. $d_n^{\text{exp}} \lesssim 3 \times 10^{-26} \text{ e cm}$ [Baker et al. '06]
- ➡ Background-free precision-laboratory for NP
(For n assuming dynamical solution for strong CP)
- ➡ Probe of energy scales beyond the direct reach of LHC

EDMs and NP

Sakharov's conditions ('67):

NP models necessarily involve new sources of CPV!

- Typically over-fulfilled by NP models
(“Significant EDMs just around the corner” always true)
- ➡ Generic one-loop contributions excluded
(→ e.g. SUSY CP-problem)
- ➡ Highly non-trivial flavour- and CPV-structure required
- ➡ Sensitivity to two-loop contributions

EDMs important on two levels:

- “Smoking-Gun-level”: Visible EDMs proof for NP
- Quantitative level:
Setting limits/determining parameters
 - ➡ Theory uncertainties are important!

Back to basics: EDMs

Classically: $\mathbf{d} = \int d^3r \rho(\mathbf{r})\mathbf{r}$, $U = \mathbf{d} \cdot \mathbf{E}$

QM: non-degenerate ground state implies $\mathbf{d} \sim \mathbf{j}$

→ $\mathbf{d} \neq \mathbf{0}$ implies T- and P-violation!

→ CP-violation for conserved CPT

→ Search for linear shift $U = d\mathbf{j} \cdot \mathbf{E}$

Historically: first measurement considered trivial by authors
Interest after observation of P- (and later CP-) violation

Non-relativistic neutral system of point-like particles:

Potential EDMs of constituents are shielded! [Sandars'65]

→ Sensitivity stems from violations of the assumptions

- Paramagnetic systems: relativistic enhancement
- Diamagnetic systems: finite-size effects

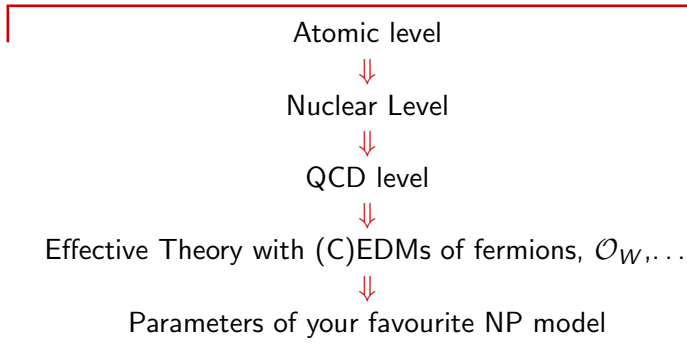
Relating NP parameters and experiment

Most stringent constraints stem from neutral systems

➡ Shielding applies

Limits usually displayed as allowed regions

➡ Conservative uncertainty estimates important



Each step potentially involves large uncertainties!

Only the last step depends on the model

Framework

Effective Lagrangian at a hadronic scale:

$$\mathcal{L} = - \sum_{f=u,d,e} \left[\frac{d_f^\gamma}{2} \mathcal{O}_f^\gamma + \frac{d_f^C}{2} \mathcal{O}_f^C \right] + C_W \mathcal{O}_W + \sum_{i,j=(q,l)} C_{ij} \mathcal{O}_{ij}^{4f},$$

in the operator basis

$$\begin{aligned} \mathcal{O}_f^\gamma &= ie\bar{\psi}_f F^{\mu\nu} \sigma_{\mu\nu} \gamma_5 \psi_f, & \mathcal{O}_f^C &= ig_s \bar{\psi}_f G^{\mu\nu} \sigma_{\mu\nu} \gamma_5 \psi_f, \\ \mathcal{O}_W &= +\frac{1}{3} f^{abc} G_{\mu\nu}^a \tilde{G}^{\nu\beta,b} G_\beta^{\mu,c}, & \mathcal{O}_{ij}^{4f} &= (\bar{\psi}_i \psi_i)(\bar{\psi}_j i\gamma_5 \psi_j) \end{aligned}$$

Options for matrix elements:

- Naive dimensional analysis[Georgi/Manohar '84] : only order-of-magnitude estimates
- Baryon χPT : not applicable for all the operators
- QCD sum rules: used here [Pospelov et al.] , uncertainties large

Theory uncertainties and the EDM of Mercury

- The most precise atomic EDM limit so far:

$$|d_{Hg}| \leq 3.1 \times 10^{-29} \text{ e cm [Griffith et al. '09]}$$

- However: difficult diamagnetic system

- Shielding efficient $\rightarrow$ sensitivity $\sim d_n, d_{TI}$

$$d_{Hg} \stackrel{\text{Atomic}}{=} d_{Hg}(S, C_{S,P}^N) \stackrel{\text{Nuclear}}{=} d_{Hg}(\bar{g}_{\pi NN}, C_{S,P}^{p,n})$$

$$\stackrel{\text{QCD}}{=} d_{Hg}(d_f^C, C_{qq'}, C_{S,P}^q)$$

- Uncertainties:

Atomic $\sim 20\%$, Nuclear $\sim \times 100\%$, QCD sum rules $\sim 100 - 200\%$

- ➡ No conservative constraint on CEDMs left! [MJ/Pich'13]

$$d_{Hg} = \left\{ -(1.0 \pm 0.2) \left((1.0 \pm 0.9) \bar{g}_{\pi NN}^{(0)} + 1.1 (1.0 \pm 1.8) \bar{g}_{\pi NN}^{(1)} \right) \right. \\ \left. + (1.0 \pm 0.1) \times 10^{-5} \left[-4.7 \tilde{C}_S + 0.49 \tilde{C}_P \right] \right\} \times 10^{-17} \text{ e cm},$$

Progress in theory necessary to fully exploit precision measurements of diamagnetic EDMs

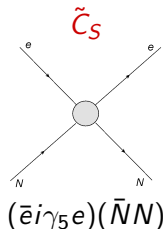
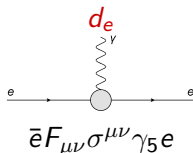
The EDM in heavy paramagnetic systems

Two main contributions, enhanced by Z^3 : [Sandars'65, Flambaum'76]

- $\tilde{C}_S$: CP-odd Electron-Nucleon interaction
- Atoms: typically polarized in external field
- Molecules: aligned in external field

For molecules: energy shift $\Delta E = \hbar\omega$ with

$$\omega = 2\pi \left(\frac{W_d^M}{2} d_e + \frac{W_c^M}{2} \tilde{C}_S \right) .$$



Molecule	$W_d^M/10^{25}\text{Hz}/e\text{ cm}$	W_c^M/kHz
YbF	-1.3 ± 0.1	-92 ± 9
ThO	-3.67 ± 0.18	-598 ± 90

[Results entering: Nayak/Chaudhuri'07,'08,'09; Dzuba et al.'11, Meyer/Bohn'08, Skripnikov et al.'13, Fleig/Nayak'14; Averages: MJ'13, MJ/Pich'14]

A model-independent limit on the electron EDM

Extracted limits for paramagnetic systems:

[Regan et al.'02, Hudson et al.'11, Baron et al.'14]

$$|d_e| \leq \left\{ \begin{array}{ll} 1.6 & (Tl) \\ 1.05 & (YbF) \\ 0.089 & (ThO) \end{array} \right\} \times 10^{-27} e \text{ cm (90\% CL)},$$

assuming **exact coefficients** and $\tilde{C}_S = 0$.

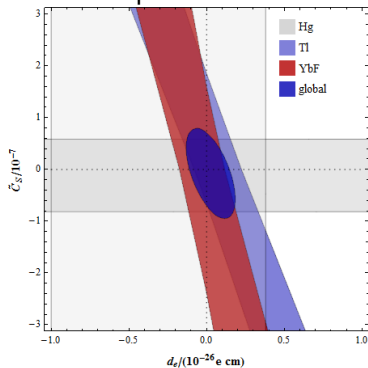
In principle: two unknowns, three measurements $\rightarrow d_e, \tilde{C}_S$

[Dzuba et al.'11, MJ'13]

- Coefficient uncertainties estimated, (5 – 10)%
- Problem: W_d^M / W_c^M similar for all three systems
 - ➡ Bounds not independent in the $d_e - \tilde{C}_S$ plane
 - ➡ Large range for d_e and $\tilde{C}_S$ separately
- Idea for $\tilde{C}_S$: **make assumption on a sub-leading level**
 - ➡ Use bound on $\tilde{C}_S$ from Mercury (conservative!) [MJ'13]

Results for d_e and $\tilde{C}_S$

pre-ThO



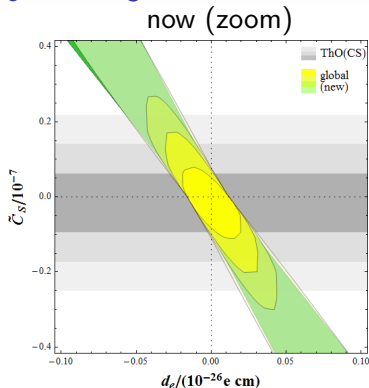
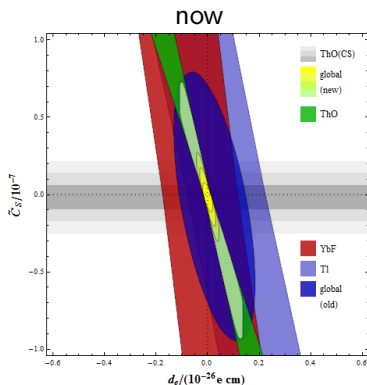
Competitive with naive extraction:

- Model-independent bounds:

$$|d_e| \leq 1.4 \times 10^{-27} \text{ e cm @95\% CL}$$

$$|\tilde{C}_S| \leq 0.72 \times 10^{-7}$$

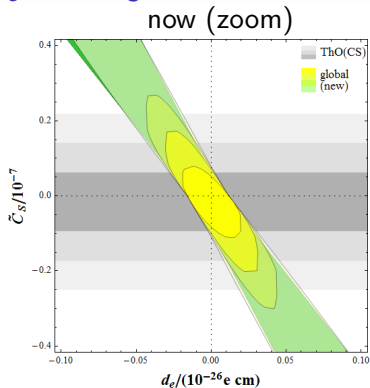
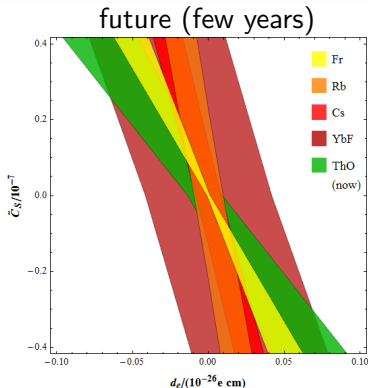
Results for d_e and $\tilde{C}_S$



Problem: ThO first “new generation” experiment

- Cancellations possible in ThO, $|d_e| \leq 1.0 \times 10^{-27} e \text{ cm}$
- Option: impose $\omega_{\text{ThO}}(\tilde{C}_S)|_{d_e=0} \leq n \times \omega_{\text{ThO}}^{\text{exp}}$, $n = 1, 2, 3 \dots$
 - ➡ $n=2$ restriction: $|d_e| \leq 0.25 \times 10^{-27} e \text{ cm}$ (95% CL)
- In the future: use additional measurements from e.g. Rb,Cs

Results for d_e and $\tilde{C}_S$



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Turning the argument around

Other limits not relevant to global fit

- ➡ Use results to conservatively bound their EDMs
(ThO not yet included)

System	Allowed range (theory)	Experimental bound on $ d_X $
Cs	$[-1.6, 2.0] \times 10^{-25}$	1.4×10^{-23} [Murthy et al.'89]
Rb	$[-3.1, 4.1] \times 10^{-26}$	1×10^{-18} [Ensberg et al.'67]
	unpublished:	(1.2×10^{-23}) [Huang-Hellinger'87]
Fr	$[-1.3, 1.5] \times 10^{-24}$	—

- ➡ **Several orders of magnitude below present limits!**

Experiments aiming at even better sensitivity:

- ➡ Important progress to be expected
- ➡ Above limits “sanity check” for future measurements

Why 2HDM?

Model-independent analysis: Too many parameters in general

EW symmetry breaking mechanism still not completely fixed:

- 1HDM minimal and elegant, but “unlikely” (SUSY, GUTs, . . .)
- 2HDM “next-to-minimal”:
 - ρ -parameter “implies” doublets
 - low-energy limit of more complete NP models
 - ➡ Model-independent element
 - simple structure, but interesting phenomenology
 - important effects in flavour observables

Could explain tensions in the flavour sector (e.g. $B \rightarrow D^{(*)} \tau \nu$)

Not an attempt at a complete theory!

Framework for 2HDM contributions

The CPV interactions of the 2nd doublet can generate EDMs

General parametrization for $H^\pm$ Yukawas, ς_i **complex matrices**:

$$\mathcal{L}_Y^{H^\pm} = -\frac{\sqrt{2}}{v} H^\pm \left\{ \bar{u} \left[V_{\varsigma_d} M_d \mathcal{P}_R - \varsigma_u M_u^\dagger V \mathcal{P}_L \right] d + \bar{\nu} \varsigma_l M_l \mathcal{P}_R l \right\} + \text{h.c.}$$

- Easily matched on your favourite model
 - ➡ M_i only choice of normalization
- $\varsigma_i \rightarrow$ **numbers**: Aligned 2HDM [Pich/Tuzon'09, MJ/Pich/Tuzon'10]
 - ➡ Comparisons with flavour data in this model

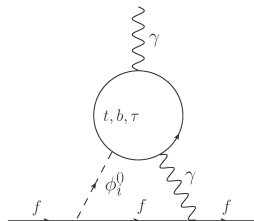
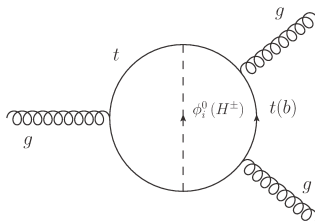
Neutral Higgs exchanges: couplings $y_i^0(\varsigma_i, V)$

- ➡ Additional CPV contributions from the potential
- ➡ Analysis depends on many unknown parameters

EDMs in 2HDMs

From necessary flavour suppression for a viable model:

- One-loop (C)EDMs: controlled (not tiny) [e.g. Buras et al. '10]
- 4-quark operators small (no $\tan^3\beta$ -enhancement)
- ➡ Two-loop graphs dominant (plus eN-vertex) [Weinberg '89, Dicus '90, Barr/Zee '90, Gunion/Wyler '90,...]
 - Weinberg diagram important for neutron EDM
 - Barr-Zee(-like) diagrams dominate the other EDMs



- ➡ Mixed-up power counting, sensitivity to UV completion

Neutral Higgs contributions in general 2HDMs

Contributions typically involve the following sum:

(f,f': fermions, F(f): family of the fermion)

$$\sum_i \operatorname{Re} \left(y_f^{\varphi_i^0} \right) \operatorname{Im} \left(y_{f'}^{\varphi_i^0} \right) = \pm \operatorname{Im} \left[(\varsigma_{F(f)}^*)_{ff} (\varsigma_{F(f')})_{f'f'} \right]$$

- R.h.s. independent of the Higgs potential
 - Vanishes for equal fermions (universality: equal family)
 - Modified by mass-dependent weight factors. . .
- ➡ but holds for degenerate masses **and** decoupling limit

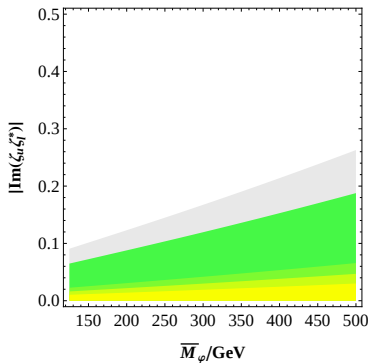
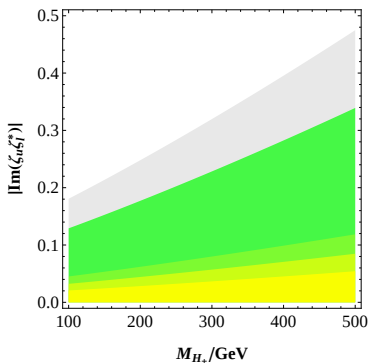
CPV in the potential tends to have smaller impact

➡ Approximation for phenomenological analysis:

$$\sum_i f(M_{\varphi_i^0}) \operatorname{Re} \left(y_f^{\varphi_i^0} \right) \operatorname{Im} \left(y_{f'}^{\varphi_i^0} \right) \rightarrow \pm f(\overline{M}_\varphi) \operatorname{Im} \left[(\varsigma_{F(f)}^*)_{ff} (\varsigma_{F(f')})_{f'f'} \right] .$$

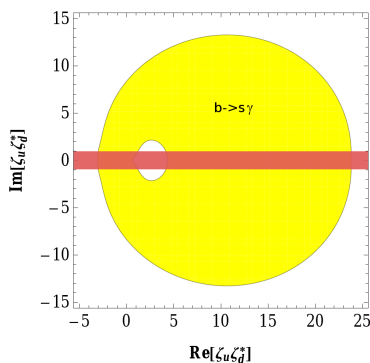
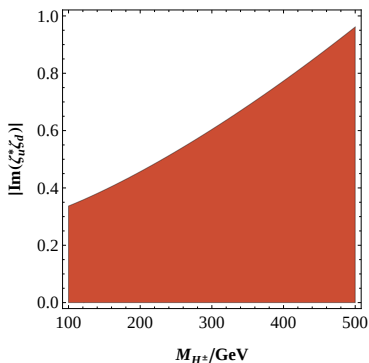
Bounds from the electron EDM

- Contributions via Barr-Zee diagrams [Bowser-Chao et al.'97]
- Sensitivity to $d_e \sim \text{Im}(\varsigma_{u,33}^* \varsigma_{l,11})$
- Bounds $\text{Im}(\varsigma_u^* \varsigma_l) \lesssim \mathcal{O}(0.1)$
 - ➡ Not too unnatural with mass normalization
- Implies $\text{Im}(\varsigma_l \varsigma_u^*) / M_{H^\pm}^2 \leq \times 10^{-5} \text{GeV}^{-2}$ (universal ς_i 's)
 - ➡ A factor **1000** stronger than (semi)leptonic constraints!



Bounds from the neutron EDM

- Size of Weinberg (charged) and Barr-Zee (neutral) similar
 - So far no fine-tuning necessary
 - Next-generation experiments will test critical parameter space
 - Constraint from Hg potentially a few times stronger
 - Comparison with $b \rightarrow s\gamma$: large impact! [MJ/Pich'14, MJ/Li/Pich'12]
- ➡ EDMs restrict CPV in other modes



Conclusions and outlook

- CPV-sector of NP models uniquely constrained by EDMs
- Quantitative results require close look at theory uncertainties
 - ➡ Use conservative limits, allowing for cancellations
- Robust, model-independent limit on electron EDM:

$$|d_e| \leq 1.0(0.25) \times 10^{-27} e \text{ cm} \quad (95\% \text{ CL}, Hg/n = 2)$$

- ➡ Issue: 2nd competitive measurement missing
- General discussion of 2HDM constraints possible
 - ➡ ς_i key parameters, CPV from potential suppressed
- Very strong constraints from EDMs
 - ➡ Flavour suppression just sufficient
 - ➡ CPV in other observables strongly restricted
- Lots of new EDM-results to come (atoms and molecules)
 - ➡ Renders use of d_{Hg} or fine-tuning arguments unnecessary
 - ➡ Might turn limits into determinations

Thank you!

Backup slides

- 2HDM Framework
- Limits on $|d_e|$ and $|\tilde{C}_S|$
- Expected limits from paramagnetic systems

Framework for 2HDM contributions

In 2HDMs, CPV in new interactions can generate EDMs!

Parametrization for $H^\pm$ Yukawas, ς_i complex:

$$\mathcal{L}_Y^{H^\pm} = -\frac{\sqrt{2}}{v} H^\pm \left\{ \bar{u} \left[V_{\varsigma d} M_d \mathcal{P}_R - \varsigma_u M_u^\dagger V \mathcal{P}_L \right] d + \bar{\nu} \varsigma_l M_l \mathcal{P}_R l \right\} + \text{h.c.}$$

- General for coupling **matrices** ς_i (M_i choice of normalization)
- **Numbers** ς_i : Aligned 2HDM [Pich/Tuzon'09, MJ/Pich/Tuzon'10]
- Easily matched on your favourite model

For mass eigenstates $\varphi_i^0 = \{h, H, A\}$, $\mathcal{M}_{\text{diag}}^2 = \mathcal{R} \mathcal{M}^2 \mathcal{R}^T$, we have

$$\mathcal{L}_Y^{\varphi_i^0} = -\frac{1}{v} \sum_{\varphi, f} \varphi_i^0 \bar{f} y_f^{\varphi_i^0} M_f \mathcal{P}_R f + \text{h.c.},$$

$$y_f^{\varphi_i^0} = \mathcal{R}_{i1} + (\mathcal{R}_{i2} \pm i \mathcal{R}_{i3}) \left(\varsigma_{F(f)}^{(*)} \right)_{ff} \quad \text{for} \quad F(f) = d, l(u).$$

For neutrals: additional CPV contributions from the potential!

Results for d_e and $\tilde{C}_S$ from ThO [MJ/Pich'14]

Input	$ d_e $ limit (95% CL)	$ \tilde{C}_S $ limit (95% CL)
Result w/o ThO [MJ'13]	$1.4 \times 10^{-27} e \text{ cm}$	7×10^{-8}
Including ThO, $\tilde{C}_S$ Hg	$1.0 \times 10^{-27} e \text{ cm}$	7×10^{-8}
Including ThO, $\tilde{C}_S$ ThO ($n = 3$)	$0.35 \times 10^{-27} e \text{ cm}$	2.3×10^{-8}
Including ThO, $\tilde{C}_S$ ThO ($n = 2$)	$0.25 \times 10^{-27} e \text{ cm}$	1.6×10^{-8}
Including ThO, $\tilde{C}_S$ ThO ($n = 1$)	$0.16 \times 10^{-27} e \text{ cm}$	0.8×10^{-8}
ThO only, $\tilde{C}_S = 0$, 90% CL	$0.089 \times 10^{-27} e \text{ cm}^{\dagger, \ddagger}$	$0.6 \times 10^{-8, \ddagger}$

Table : New limits on the electron EDM and $\tilde{C}_S$, including the measurement in the ThO system [Baron et al,'13] . † : Using W_d from [Skripnikov et al.'13] . ‡ : Theory errors neglected.

Expected limits from paramagnetic atoms

System	Expected limit (e cm)
^{133}Cs	$\mathcal{O}(10^{-26}/10^{-27})$ [Amini et al.'07, Kittle et al.'04, Weiss et al.'03]
^{85}Rb	$\mathcal{O}(10^{-27}/10^{-28})$ [Weiss et al.'03]
^{210}Fr	$\mathcal{O}(10^{-26}/10^{-29})$ [Sakemi et al.'11, Wundt et al.'12]
YbF	$\mathcal{O}(10^{-22}/10^{-23-24})$ [Kara et al.'12]

Table : Short-term/mid-term expected sensitivities for paramagnetic atoms.