Café com Física:

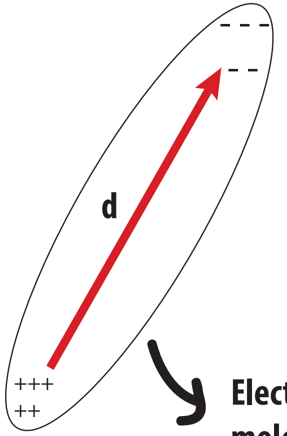
Constraining dimension-six nonminimal Lorentz-violating electron-nucleon interactions with **EDM physics**

JONAS ARAÚJO

UNIVERSIDADE DE COIMBRA,
DECEMBER 2019

For starters, what is EDM?

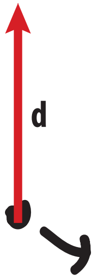
- **EDM** stands for **E**lectric **D**ipole **M**oment
- We're talking about the EDM of elementary particles!



Electrically polarized molecule

P-odd
T-even

$\neq$



Elementary particle

P-even
T-odd

$$\boldsymbol{d} = \eta\left(\frac{q}{2mc}\right)\boldsymbol{S}$$

EDM Hamiltonian:

$$-\boldsymbol{d}\cdot\boldsymbol{E}$$

Violates P and T
(**and CP**, if the CPT theorem holds)

$$P(\boldsymbol{d}\cdot\boldsymbol{E}) \rightarrow -\boldsymbol{d}\cdot\boldsymbol{E} \qquad T(\boldsymbol{d}\cdot\boldsymbol{E}) \rightarrow -\boldsymbol{d}\cdot\boldsymbol{E}$$

Why is this important?
I'm glad you asked ;)

EDMs and discrete symmetries

- C and CP violations are fundamental ingredients to explain the matter – anti-matter asymmetry in the universe!
- **The Sakharov conditions:**

1. Baryon number (B) violation
2. Sources of C and CP violation (**EDM searches fit here!**)
3. Interactions out of thermal equilibrium

- C and CP violation sources in the SM are too small!
- There must be **new Physics** or **unknown mechanisms in the SM**!

Current Status: Experiments *versus* SM

- For an electronic EDM, the SM prediction is of around

$$|d_e^{\mathrm{MP}}| \approx 10^{-38}\, e \cdot \mathrm{cm}\ ,$$

- The experiments probe up until [**Nature (London) 562, 355 (2018)**]

$$|d_e| < 1.1 \times 10^{-29} e\ \mathrm{cm}$$

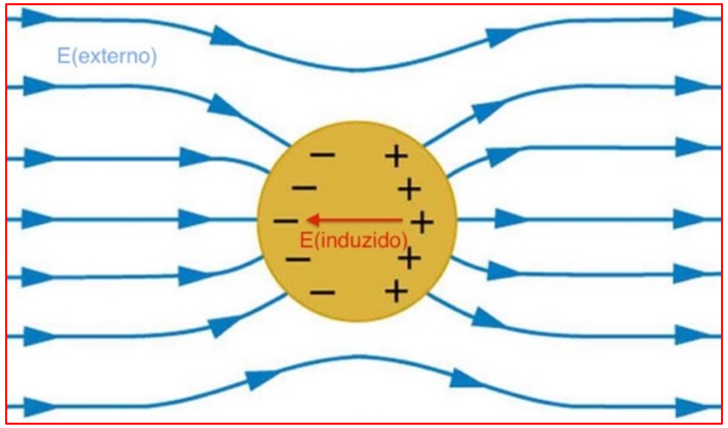
- Two scenarios may fit in these 9 orders of magnitude:

1. **Experiments become increasingly precise and confirm the SM prediction**
2. **EDMs are detected above the SM prediction >>> New Physics!**

Experimental detection

- Typical experiments attempt to detect EDM in atomic systems (why?)
- An electric field is applied on the atom/molecule, but a problem rises!

- The external electric field is counter-balanced by the internal field induced by polarization



The molecule's constituents feel NO ELECTRIC FIELD (in average)

No net electric field >>>>> **No EDM-induced energy shift**

This implies EDMs are undetectable in atomic systems!
This is known as the **Schiff's Theorem**

Bypassing Schiff's Theorem

- **Schiff's theorem has 3 conditions of validity**:

1. Electrostatic interactions only
2. Point-like particles only
3. Nonrelativistic systems

It turns out an EDM is detectable if any of those conditions is not satisfied

1. The experiments are done using **electric AND magnetic fields**!
2. A nuclear EDM is detectable if the nucleus is not point-like (residual **Schiff Moment**)
3. An **electronic EDM is detectable** (and much enhanced) in **relativistic scenarios**

Who carries the EDM in a molecule?

- In an atom, an EDM may be due to:

1. Intrinsic properties of the electrons or nucleons OR
2. The interaction between them

- We will focus on the possibility 2, that is, **electron-nucleon (e-N) couplings**

Electron-nucleon couplings

- These couplings involve 4 spinors and have the general form

$$\left(\bar{N}\Gamma_1 N\right)\left(\bar{\psi}\Gamma_2\psi\right)$$

- They have mass dimension of at least **6**

- Each factor in parenthesis is a Dirac bilinear

- Only the ones with **P- and T-odd** components are viable candidates!

TABLE III. Behavior of Dirac bilinears under discrete symmetry operators.

	$\bar{\psi}\psi$	$\bar{\psi}i\gamma_5\psi$	$\bar{\psi}\gamma^0\psi$	$\bar{\psi}\gamma^i\psi$	$\bar{\psi}\gamma^0\gamma_5\psi$	$\bar{\psi}\gamma^i\gamma_5\psi$	$\bar{\psi}\sigma^{0i}\psi$	$\bar{\psi}\sigma^{ij}\psi$
P	$+$	$-$	$+$	$-$	$-$	$+$	$-$	$+$
T	$+$	$-$	$+$	$-$	$+$	$-$	$+$	$-$
C	$+$	$+$	$-$	$-$	$+$	$+$	$-$	$-$

Electron-nucleon couplings

- In the usual scenario, the candidates are:

Example!

P- and **T**-odd

	$\bar{\psi}\psi$	$\bar{\psi}i\gamma_5\psi$
P	$+$	$-$
T	$+$	$-$
C	$+$	$+$

$\bar{N}N \cdot \bar{e}\gamma^5 e$	S-PS (scalar-pseudoscalar)
$\bar{N}\gamma^\mu N \cdot \bar{e}\gamma_\mu\gamma^5 e$	V-A (vector-axial vector)
$\bar{N}\sigma^{\mu\nu}N \cdot \bar{e}\sigma_{\mu\nu}\gamma^5 e$	T-PT (tensor-pesudotensor)
$\bar{N}\gamma^\mu\gamma^5 N \cdot \bar{e}\gamma_\mu e$	A-V (axial vector-vector)
$\bar{N}\gamma^5 N \cdot \bar{e}e$	PS-S (pseudoscalar-scalar).

- But only the FIRST, THIRD and FIFTH contain **P- and T-odd components**

Effective Lagrangian

$$\mathcal{L}_{CP} = -\frac{G_F}{\sqrt{2}} \sum_j \left[C_S \bar{N}_j N_j \bar{\psi} i\gamma^5 \psi + C_P \bar{N}_j i\gamma_5 N_j \bar{\psi}\psi - \frac{1}{2}\epsilon_{\mu\nu\alpha\beta} C_T \bar{N}_j \sigma^{\mu\nu} N_j \bar{\psi}\sigma^{\alpha\beta}\psi \right]$$

Electron-nucleon couplings: an example

- Now we'll outline how to read an EDM contribution from an effective 4-spinor Lagrangian
- Consider the (dominant) term

$$\mathcal{L}_{CP} = -\frac{G_F}{\sqrt{2}} \sum_j C_S \bar{N}_j N_j \bar{\psi} i \gamma_5 \psi$$

- **First we apply the nonrelativistic limit for the nucleons**

$$\bar{N}_j N_j = \begin{pmatrix} \phi_N^* & \chi_N^* \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} \phi_N \\ \chi_N \end{pmatrix}$$

$$\approx |\phi_N|^2 \ ,$$

$$n(\boldsymbol{r}) = |\phi_N|^2$$

Nucleon's probability density!

Remaining (electron's) Lagrangian

$$\mathcal{L}_{CP-e} = -\frac{G_F}{\sqrt{2}} C_S A n(\boldsymbol{r}) \bar{\psi} i \gamma_5 \psi$$

Note the nucleons' densities added up **coherently** to A.n(**r**)

Electron-nucleon couplings: an example

- The electron's Hamiltonian is then

$$\mathcal{H}_{CP}\psi = i\frac{G_F}{\sqrt{2}}C_S A n(\boldsymbol{r})\gamma^0\gamma_5\psi$$

- Next, we need to find the **energy shift** this Hamiltonian piece generates:

$$\Delta E = \langle\Psi|\mathcal{H}_{CP}|\Psi\rangle$$

Where the wavefunction is that of the electron in an atom under an external electric field!

A little digression is needed to find $|\Psi\rangle$

Electron-nucleon couplings: an example

- Without an external electric field, the electron's Hamiltonian is

$$H_0 = \boldsymbol{\alpha} \cdot \boldsymbol{p} + m\gamma^0 - e\Phi_{\text{int}}(\boldsymbol{r})$$

Modified Tiez-potential

$$\Phi_{\text{int}}(\boldsymbol{r}) = \begin{cases} r > R_N & \frac{(Z-1)}{r(1+br)^2} \exp(-ar) + \frac{1}{r} \\ r < R_N & \left[\frac{(Z-1)}{(1+br)^2} \exp(-ar) + 1\right] \left(3 - \frac{r^2}{R_N^2}\right) \frac{1}{2R_N} \end{cases}$$

Whose solutions are $|\psi_n\rangle$

- As an external electric field is applied, the ground state is modified as

$$|\Psi\rangle = |\psi_0\rangle + eE_z|\eta\rangle$$

Where, by perturbation theory

$$|\eta\rangle = \sum_{n \neq 0} \frac{|\psi_n\rangle\langle\psi_n|z|\psi_0\rangle}{E_0 - E_n}$$

Note it has opposite parity if compared to the ground state

Electron-nucleon couplings: an example

- The energy shift is then

$$\Delta E = eE_z\langle\psi_0|\mathcal{H}_{CP}|\eta\rangle + eE_z\langle\eta|\mathcal{H}_{CP}|\psi_0\rangle$$
$$= 2eE_z\Re\left(\langle\psi_0|\mathcal{H}_{CP}|\eta\rangle\right) \ ,$$

- So that we identify

$$\Delta E = d_{\mathrm{equiv}}E_z$$

The shift is proportional to E_{ext}! The constant factor should be equivalent to an EDM.

$$d_{\mathrm{equiv}} = 2e\Re\left(\langle\psi_0|\mathcal{H}_{CP}|\eta\rangle\right)$$

- Let us make a few comments on these spinors

Electron-nucleon couplings: an example

- The spinors of the ground state $|\psi_0\rangle$ and $|\eta\rangle$ are solutions of the Dirac and of the Sternheimer equations, respectively
- We will use data on the thallium atom (A=205 and Z=81)

The ground state is

$$(\psi_0)^{l=1}_{J=\frac{1}{2},m=\frac{1}{2}} = \begin{pmatrix} \frac{i}{r} G_{l,J=\frac{1}{2}}(r)\phi^{l}_{\frac{1}{2},\frac{1}{2}} \\ \frac{1}{r} F_{l,J=\frac{1}{2}}(r)\,(\boldsymbol{\sigma}\cdot\hat{\boldsymbol{r}})\,\phi^{l}_{\frac{1}{2},\frac{1}{2}} \end{pmatrix}$$

In these spinors we use:

$$\phi^{l=0}_{\frac{1}{2},\frac{1}{2}} = \begin{pmatrix} Y^0_0 \\ 0 \end{pmatrix} \ , \quad \phi^{l=1}_{\frac{1}{2},\frac{1}{2}} = \begin{pmatrix} \sqrt{\frac{1}{3}} Y^0_1 \\ -\sqrt{\frac{2}{3}} Y^1_1 \end{pmatrix}$$

while the first-order correction is

$$\eta^{l=0}_{J=\frac{1}{2},m=\frac{1}{2}} = \begin{pmatrix} \frac{i}{r} G^S_{l,J=\frac{1}{2}}(r)\phi^{l}_{\frac{1}{2},\frac{1}{2}} \\ \frac{1}{r} F^S_{l,J=\frac{1}{2}}(r)\,(\boldsymbol{\sigma}\cdot\hat{\boldsymbol{r}})\,\phi^{l}_{\frac{1}{2},\frac{1}{2}} \end{pmatrix}$$

Dirac equation

$$\frac{d}{dr}G + \frac{1}{r}G = \alpha\left(W_0 + \frac{2}{\alpha^2} + \Phi_i\right)F\ ,$$

$$\frac{d}{dr}F - \frac{1}{r}F = -\alpha\,(W_0 + \Phi_i)\,G\ ,$$

Sternheimer equation

$$\frac{d}{dr}G + \frac{1}{r}G = \alpha\left(W_0 + \frac{2}{\alpha^2} + \Phi_i\right)F\ ,$$

$$\frac{d}{dr}F - \frac{1}{r}F = -\alpha\,(W_0 + \Phi_i)\,G\ ,$$

Electron-nucleon couplings: an example

- Using these spinors, we get

$$d_{\text{equiv}} = 2e\frac{G_F}{\sqrt{2}}\frac{3AC_S}{4\pi R_N^3}\int_0^{R_N}\left(G\,F^S + G^S\,F\right)dr$$

- Using the numerical estimates in [B. Lee Roberts and W. J. Marciano, Lepton Dipole Moments]

$$d_{\text{equiv}} = 6.8\times 10^4 C_S G_F$$

- This contribution cannot be larger than the experimental upper limit, which implies

$$d_{\text{equiv}} = 6.8\times 10^4 C_S G_F < 1.1\times 10^{-29} e\cdot\text{cm}$$

$$\Downarrow$$

$$C_S < 7.3\times 10^{-10}$$

The Fermi constant G_F is known

Generalized electron-nucleon couplings

Now we know to read EDM contributions from the couplings;

- Next we need to generalize them using Lorentz-violating background tensors
- First let us look at the rank-1 case

$$\mathcal{L}_{\text{LV}} = (k_{XX})_\mu \left[\left(\bar{N}\, \Gamma_1\, N \right) \left(\bar{\psi}\, \Gamma_2\, \psi \right) \right]^\mu$$

⟸ Inspired by [Phys. Rev. D 99, 056016 (2019)]

- Each X stands for the **type of Dirac bilinear**: Scalar (**A**), Pseudoscalar (**P**), Vector (**V**), Axial Vector (**A**), and Tensor (**T**) (remember they have dimension-6)
- Let us have a look at the possibilities (**LOOK FOR P- and T-ODD COMPONENTS ONLY**)

Motivations?

- Non null vacuum expectation values from possible higher-energy Physics
- Anisotropic properties to the spacetime > (minute) **Lorentz Symmetry* and/or CPT violations**
- Please have a look at <<https://lorentz.sitehost.iu.edu/kostelecky/faq.html>>
- A **very versatile framework** subject to stringent experimental data

Rank-1 LV electron-nucleon couplings

TABLE I. General CPT-odd couplings with a rank-1 LV tensor and Dirac bilinears. NRL stands for the nonrelativistic limit for the nucleons (N). In this limit, the coupling component can be suppressed, "S," or not suppressed, "NS."

Coupling	P-odd, T-odd piece	NRL	EDM
$(k_{SV})_\mu(\bar{N}N)(\bar{\psi}\gamma^\mu\psi)$	$(k_{SV})_i(\bar{N}N)(\bar{\psi}\gamma^i\psi)$	NS	Yes
$(k_{VS})_\mu(\bar{N}\gamma^\mu N)(\bar{\psi}\psi)$	$(k_{VS})_i(\bar{N}\gamma^i N)(\bar{\psi}\psi)$	S	...
$(k_{VP})_\mu(\bar{N}\gamma^\mu N)(\bar{\psi}i\gamma_5\psi)$	$(k_{VP})_0(\bar{N}\gamma^0 N)(\bar{\psi}i\gamma_5\psi)$	NS	Yes
$(k_{PV})_\mu(\bar{N}i\gamma_5 N)(\bar{\psi}\gamma^\mu\psi)$	$(k_{PV})_0(\bar{N}\gamma_5 N)(\bar{\psi}\gamma^0\psi)$	S	...
$(k_{SA})_\mu(\bar{N}N)(\bar{\psi}\gamma^\mu\gamma_5\psi)$	None	...	...
$(k_{AS})_\mu(\bar{N}\gamma^\mu\gamma_5 N)(\bar{\psi}\psi)$	None	...	...
$(k_{PA})_\mu(\bar{N}i\gamma_5 N)(\bar{\psi}\gamma^\mu\gamma_5\psi)$	None	...	...
$(k_{AP})_\mu(\bar{N}\gamma^\mu\gamma_5 N)(\bar{\psi}i\gamma_5\psi)$	None	...	...

We could try other possibilities, but they are redundant

(particular cases of rank-3 couplings!)

TABLE II. Redundant CPT-odd couplings with a rank-1 LV tensor and matrixes γ^μ, $\sigma^{\mu\nu}$, and γ^5.

Coupling	P-odd, T-odd piece	NRL	EDM
$(k_{VT})_\nu(\bar{N}\gamma_\mu N)(\bar{\psi}\sigma^{\mu\nu}\psi)$	None	...	...
$(k_{AT})_\nu(\bar{N}\gamma_\mu\gamma_5 N)(\bar{\psi}\sigma^{\mu\nu}\psi)$	$(k_{AT})_0(\bar{N}\gamma_i\gamma_5 N)(\bar{\psi}\sigma^{i0}\psi)$	NS	Yes
$(k_{TV})_\nu(\bar{N}\sigma^{\mu\nu}N)(\bar{\psi}\gamma_\mu\psi)$	None	...	...
$(k_{TA})_\nu(\bar{N}\sigma^{\mu\nu}N)(\bar{\psi}\gamma_\mu\gamma_5\psi)$	$(k_{TA})_0(\bar{N}\sigma^{i0}N)(\bar{\psi}\gamma_i\gamma_5\psi)$	S	...

Free Lorentz-index >>>> More possibilities!

Rank-1 electron-nucleon Couplings

- There are 2 contributions arising from rank-1 couplings

$$H_{\mathrm{LV}e-1} = [-(k_{SV})_i\, A\gamma^0\gamma^i - (k_{VP})_0\, Ai\gamma^0\gamma_5] \cdot n(\boldsymbol{r})$$

- According to the results

$$\langle\psi_0|\gamma^0\gamma^i|\eta\rangle = i\delta_{i3}\int_0^{R_N}\left[\frac{1}{3}F^S(r)G(r) + G^S(r)F(r)\right]dr\ ,$$

$$\langle\psi_0|\gamma_5|\eta\rangle = i\int_0^{R_N}\left[-F^S(r)G(r) + G^S(r)F(r)\right]dr\ ,$$

$$\langle\psi_0|i\gamma^i|\eta\rangle = \delta_{i3}\int_0^{R_N}\left[-\frac{1}{3}F^S(r)G(r) + G^S(r)F(r)\right]dr\ ,$$

Later we'll assume the 3rd is approximately this (**known**) integral

$$\int_0^{R_N}\left[F^S(r)G(r) + G^S(r)F(r)\right]dr$$

- Only the k_{VP} contribution is real in $\frac{\Delta E}{E_z} = 2e\Re\left[\langle\psi_0|H_{P,T}|\eta\rangle\right] \equiv d_{\mathrm{equiv}}$. Its contribution is:

$$|d_{\text{1-equiv}}| = 2e\,(k_{VP})_0\,\frac{3A}{4\pi R_N^3}\int_0^{R_N}\left[F^S(r)G(r) + G^S(r)F(r)\right]dr$$

The only contribution of rank-1

$$|\,(k_{VP})_0\,| < 1.6\times 10^{-15}\,(\mathrm{GeV})^{-2}.$$

Rank-2 electron-nucleon Couplings

- For the rank-2 case, the possibilities are

Coupling	P-odd and T-odd piece	NRL	EDM
Rank-2			
$(k_{VV})_{\mu\nu}(\bar{N}\gamma^{\mu}N)(\bar{\psi}\gamma^{\nu}\psi)$	$(k_{VV})_{i0}(\bar{N}\gamma^{i}N)(\bar{\psi}\gamma^{0}\psi)$	S	...
	$(k_{VV})_{0i}(\bar{N}\gamma^{0}N)(\bar{\psi}\gamma^{i}\psi)$	NS	Yes
$(k_{AV})_{\mu\nu}(\bar{N}\gamma^{\mu}\gamma_5 N)(\bar{\psi}\gamma^{\nu}\psi)$	None	...	...
$(k_{VA})_{\mu\nu}(\bar{N}\gamma^{\mu}N)(\bar{\psi}\gamma^{\nu}\gamma_5\psi)$	None	...	...
$(k_{AA})_{\mu\nu}(\bar{N}\gamma^{\mu}\gamma_5 N)(\bar{\psi}\gamma^{\nu}\gamma_5\psi)$	$(k_{AA})_{0i}(\bar{N}\gamma^{0}\gamma_5 N)(\bar{\psi}\gamma^{i}\gamma_5\psi)$	S	...
	$(k_{AA})_{i0}(\bar{N}\gamma^{i}\gamma_5 N)(\bar{\psi}\gamma^{0}\gamma_5\psi)$	NS	Yes
$(k_{TS})_{\mu\nu}(\bar{N}\sigma^{\mu\nu}N)(\bar{\psi}\psi)$	None	...	...
$(k_{TP})_{\mu\nu}(\bar{N}\sigma^{\mu\nu}N)(\bar{\psi}i\gamma_5\psi)$	None	...	...
$(k_{ST})_{\mu\nu}(\bar{N}N)(\bar{\psi}\sigma^{\mu\nu}\psi)$	None	...	...
$(k_{PT})_{\mu\nu}(\bar{N}i\gamma_5 N)(\bar{\psi}\sigma^{\mu\nu}\psi)$	None	...	...

2 candidates, but we'll see only 1 yields non-zero EDM

Rank-2 electron-nucleon Couplings

- The Hamiltonian arising from these two contributions are

$$H_{\mathrm{LV}e-2} = \left[-\left(k_{VV}\right)_{0i} A\gamma^0\gamma^i - \left(k_{AA}\right)_{i0} \langle\sigma^i\rangle_N \gamma_5\right] \cdot n(\boldsymbol{r})$$

- Observe

1. The first term yields no contribution because $\frac{\Delta E}{E_z} = 2e\Re\left[\langle\psi_0|H_{P,T}|\eta\rangle\right] \equiv d_{\mathrm{equiv}}$
2. The second term depends on the valence nucleon's spin, because the nucleon's spins do not add coherently! But it does not matter: its contribution is not real.

- The take-home lesson: **for couplings dependent on the nucleons' spins, the bounds are 205 larger (less stringent) than the one on rank-1 (only the valence nucleon's spin counts!).**

Rank-3 and 4 electron-nucleon Couplings

- We can extend the same analysis for the rank-3 and rank-4 cases:

Rank-3			
$(k_{VT})_{\alpha\mu\nu}(\bar{N}\gamma^\alpha N)(\bar{\psi}\sigma^{\mu\nu}\psi)$	None	$\cdots$	$\cdots$
$(k_{AT})_{\alpha\mu\nu}(\bar{N}\gamma^\alpha\gamma_5 N)(\bar{\psi}\sigma^{\mu\nu}\psi)$	$(k_{AT})_{0ij}(\bar{N}\gamma^0\gamma_5 N)(\bar{\psi}\sigma^{ij}\psi)$	S	$\cdots$
	$(k_{AT})_{i0j}(\bar{N}\gamma^i\gamma_5 N)(\bar{\psi}\sigma^{0j}\psi)$	NS	Yes
	$(k_{AT})_{ij0}(\bar{N}\gamma^i\gamma_5 N)(\bar{\psi}\sigma^{j0}\psi)$	NS	Yes
$(k_{TV})_{\alpha\mu\nu}(\bar{N}\sigma^{\mu\nu}N)(\bar{\psi}\gamma^\alpha\psi)$	None	$\cdots$	$\cdots$
$(k_{TA})_{\alpha\mu\nu}(\bar{N}\sigma^{\mu\nu}N)(\bar{\psi}\gamma^\alpha\gamma_5\psi)$	$(k_{TA})_{0ij}(\bar{N}\sigma^{ij}N)(\bar{\psi}\gamma^0\gamma_5\psi)$	NS	Yes
	$(k_{TA})_{i0j}(\bar{N}\sigma^{0j}N)(\bar{\psi}\gamma^i\gamma_5\psi)$	S	$\cdots$
	$(k_{TA})_{ij0}(\bar{N}\sigma^{j0}N)(\bar{\psi}\gamma^i\gamma_5\psi)$	S	$\cdots$
Rank-4			
$(k_{TT})_{\alpha\beta\mu\nu}(\bar{N}\sigma^{\alpha\beta}N)(\bar{\psi}\sigma^{\mu\nu}\psi)$	$(k_{TT})_{0ijk}(\bar{N}\sigma^{0i}N)(\bar{\psi}\sigma^{jk}\psi)$	S	$\cdots$
	$(k_{TT})_{i0jk}(\bar{N}\sigma^{i0}N)(\bar{\psi}\sigma^{jk}\psi)$	S	$\cdots$
	$(k_{TT})_{ij0k}(\bar{N}\sigma^{ij}N)(\bar{\psi}\sigma^{0k}\psi)$	NS	Yes
	$(k_{TT})_{ijk0}(\bar{N}\sigma^{ij}N)(\bar{\psi}\sigma^{k0}\psi)$	NS	Yes

We found, for example: $|(k_{AT})_{i03}| < 3.2\times 10^{-13}\ (\mathrm{GeV})^{-2}$

Note this bound is 205 times larger than the one we found for the rank-1 case: $1.6\times 10^{-15}\ (\mathrm{GeV})^{-2}$.

Rank-3 and 4 electron-nucleon Couplings

- The Hamiltonian contributions from the rank-3 and rank-4 cases

$$H_{\text{LVe}-3} = [(k_{AT})_{i0j}\langle\sigma^i\rangle_N i\gamma^0\alpha^j - (k_{AT})_{ij0}\langle\sigma^i\rangle_N i\gamma^0\alpha^j - (k_{TA})_{0ij}\epsilon_{ijk}\langle\sigma^k\rangle_N\gamma_5]\cdot n(\boldsymbol{r}),$$

$$H_{\text{LVe}-4} = [-(k_{TT})_{ij0k}\epsilon_{ijl}\langle\sigma^l\rangle_N i\gamma^0\alpha^k + (k_{TT})_{ijk0}\epsilon_{ijl}\langle\sigma^l\rangle_N i\gamma^0\alpha^k]\cdot n(\boldsymbol{r}),$$

Bounds on rank-3 tensors:

$$|(k_{AT})_{i03}| < 3.2\times10^{-13}\ (\text{GeV})^{-2},$$
$$|(k_{AT})_{i30}| < 3.2\times10^{-13}\ (\text{GeV})^{-2},$$

Redefining:

$$(k_{TT})_{ij0k}\epsilon_{ijl} = (K_{TT})_{0kl}.$$

Bounds on rank-4 tensors:

$$|(K_{TT})_{03l}| < 3.2\times10^{-13}\ (\text{GeV})^{-2},$$
$$|(K_{TT})_{30l}| < 3.2\times10^{-13}\ (\text{GeV})^{-2}.$$

Sidereal Variations

- The LV tensors are not constant in the Lab's Reference Frame (RF)
- The closest to an inertial RF we got is the Sun >>> A transformation is needed!
- It turns out that, for not-so-long-experiments, we only need a rotation!

$$B^{(\text{Lab})}_{\mu\nu} = \mathcal{R}_{\mu\alpha}\mathcal{R}_{\nu\beta}B^{(\text{Sun})}_{\alpha\beta}$$

$$R_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\chi\cos\Omega t & \cos\chi\sin\Omega t & -\sin\chi \\ 0 & -\sin\Omega t & \cos\Omega t & 0 \\ 0 & \sin\chi\cos\Omega t & \sin\chi\sin\Omega t & \cos\chi \end{pmatrix}$$

Chi: Lab's colatitude

Omega: Earth's rotation angular velocity

Next we time-average them in the Sun's RF.

Not all of them survive this step; here goes a list of the ones that do

Sidereal Variations

TABLE V. Bounds on the LV tensors of ranks ranging from 1 to 4.

Component	Upper bound
$\left\lvert (k_{VP})_0^{(\mathrm{Sun})} \right\rvert$	$1.6\times10^{-15}\ (\mathrm{GeV})^{-2}$
$\left\lvert \frac{1}{4}\left[(k_{AT})_{101}^{(\mathrm{Sun})}+(k_{AT})_{202}^{(\mathrm{Sun})}-2(k_{AT})_{303}^{(\mathrm{Sun})}\right]\sin 2\chi \right\rvert$	$3.2\times10^{-13}(\mathrm{GeV})^{-2}$
$\left\lvert \left[-(k_{AT})_{102}^{(\mathrm{Sun})}+(k_{AT})_{201}^{(\mathrm{Sun})}\right]\sin\chi \right\rvert$	$3.2\times10^{-13}\ (\mathrm{GeV})^{-2}$
$\left\lvert \left[\frac{1}{2}\left((k_{AT})_{101}^{(\mathrm{Sun})}+(k_{AT})_{202}^{(\mathrm{Sun})}\right)\sin^2\chi+(k_{AT})_{303}^{(\mathrm{Sun})}\cos^2\chi\right] \right\rvert$	$3.2\times10^{-13}\ (\mathrm{GeV})^{-2}$
$\left\lvert \frac{1}{4}\left[(k_{AT})_{110}^{(\mathrm{Sun})}+(k_{AT})_{220}^{(\mathrm{Sun})}-2(k_{AT})_{330}^{(\mathrm{Sun})}\right]\sin 2\chi \right\rvert$	$3.2\times10^{-13}\ (\mathrm{GeV})^{-2}$
$\left\lvert \left[-(k_{AT})_{120}^{(\mathrm{Sun})}+(k_{AT})_{210}^{(\mathrm{Sun})}\right]\sin\chi \right\rvert$	$3.2\times10^{-13}\ (\mathrm{GeV})^{-2}$
$\left\lvert \left[\frac{1}{2}\left((k_{AT})_{110}^{(\mathrm{Sun})}+(k_{AT})_{220}^{(\mathrm{Sun})}\right)\sin^2\chi+(k_{AT})_{330}^{(\mathrm{Sun})}\cos^2\chi\right] \right\rvert$	$3.2\times10^{-13}\ (\mathrm{GeV})^{-2}$
$\left\lvert \frac{1}{4}\left[(K_{TT})_{011}^{(\mathrm{Sun})}+(K_{TT})_{022}^{(\mathrm{Sun})}-2(K_{TT})_{033}^{(\mathrm{Sun})}\right]\sin 2\chi \right\rvert$	$3.2\times10^{-13}\ (\mathrm{GeV})^{-2}$
$\left\lvert \left[(K_{TT})_{012}^{(\mathrm{Sun})}-(K_{TT})_{021}^{(\mathrm{Sun})}\right]\sin\chi \right\rvert$	$3.2\times10^{-13}\ (\mathrm{GeV})^{-2}$
$\left\lvert \left[\frac{1}{2}\left((K_{TT})_{011}^{(\mathrm{Sun})}+(K_{TT})_{022}^{(\mathrm{Sun})}\right)\sin^2\chi+(K_{TT})_{033}^{(\mathrm{Sun})}\cos^2\chi\right] \right\rvert$	$3.2\times10^{-13}\ (\mathrm{GeV})^{-2}$
$\left\lvert \frac{1}{4}\left[(K_{TT})_{101}^{(\mathrm{Sun})}+(K_{TT})_{202}^{(\mathrm{Sun})}-2(K_{TT})_{303}^{(\mathrm{Sun})}\right]\sin 2\chi \right\rvert$	$3.2\times10^{-13}\ (\mathrm{GeV})^{-2}$
$\left\lvert \left[(K_{TT})_{102}^{(\mathrm{Sun})}-(K_{TT})_{201}^{(\mathrm{Sun})}\right]\sin\chi \right\rvert$	$3.2\times10^{-13}\ (\mathrm{GeV})^{-2}$
$\left\lvert \left[\frac{1}{2}\left((K_{TT})_{101}^{(\mathrm{Sun})}+(K_{TT})_{202}^{(\mathrm{Sun})}\right)\sin^2\chi+(K_{TT})_{303}^{(\mathrm{Sun})}\cos^2\chi\right] \right\rvert$	$3.2\times10^{-13}\ (\mathrm{GeV})^{-2}$

- These are the first bounds on these coefficients, which where recently proposed by Kostelecky;
- Next we comment on a few other couplings we haven't covered

These results were published in

PHYSICAL REVIEW D **100,** 015046 (2019)

Constraining dimension-six nonminimal Lorentz-violating electron-nucleon interactions with EDM physics

Jonas B. Araujo,[1,2,*] A. H. Blin,[3,†] Marcos Sampaio,[2,4,‡] and Manoel M. Ferreira, Jr.[1,§]
[1]*Departamento de Física, Universidade Federal do Maranhão, Campus Universitário do Bacanga, São Luís—MA, 65080-805, Brazil*
[2]*Centre for Particle Theory, University of Durham, Durham, DH1 3LE, United Kingdom*
[3]*CFisUC, Department of Physics, University of Coimbra, P-3004-516 Coimbra, Portugal*
[4]*CCNH, Universidade Federal do ABC, 09210-580, Santo André—SP, Brazil*

Comments on other couplings

- Kostelecky's paper contains terms as

$$(k_{SS})(\bar{N}N)(\bar{\psi}\psi), \quad (k_{PP})(\bar{N}i\gamma_5 N)(\bar{\psi}i\gamma_5\psi),$$
$$(k_{SP})(\bar{N}N)(\bar{\psi}i\gamma_5\psi), \quad (k_{PS})(\bar{N}i\gamma_5 N)(\bar{\psi}\psi),$$

- These are not LV. In fact, one of them is identical to the usual Scalar-Pseudoscalar contribution

$$\mathcal{L}^{(6)}_{\psi\psi} = i(\kappa_{SP})(\bar{\psi}\psi)(\bar{\psi}\gamma^5\psi).$$

Is identical to

$$\mathcal{L}_{CP} = -\frac{G_F}{\sqrt{2}}\sum_j C_S \bar{N}_j N_j \bar{\psi} i\gamma_5 \psi$$

$$\kappa_{SP} < 1.6\times 10^{-15}\ (\mathrm{GeV})^{-2}.$$

Also, we consider different spinors, so our possibilities double!

Future Perspectives

- Improve bounds by evaluating the integral:

$$\langle \psi_0 | i\gamma^i | \eta \rangle = \delta_{i3} \int_0^{R_{\text{Nucleus}}} \left[-\frac{1}{3} F^S(r) G(r) + G^S(r) F(r) \right] dr,$$

→ Numerical issues!

- What if we consider only usual couplings:

$$\bar{N}N \cdot \bar{e}\gamma^5 e$$
$$\bar{N}\gamma^\mu N \cdot \bar{e}\gamma_\mu \gamma^5 e$$
$$\bar{N}\sigma^{\mu\nu} N \cdot \bar{e}\sigma_{\mu\nu}\gamma^5 e$$
$$\bar{N}\gamma^\mu \gamma^5 N \cdot \bar{e}\gamma_\mu e$$
$$\bar{N}\gamma^5 N \cdot \bar{e}e$$

And then correct the electron's spinor by a dimension-5 coupling?

$$\mathcal{L}^{(5)}_{\psi F} \quad -\tfrac{1}{2} m_F^{(5)\alpha\beta} F_{\alpha\beta} \overline{\psi}\psi - \tfrac{1}{2} i m_{5F}^{(5)\alpha\beta} F_{\alpha\beta} \overline{\psi}\gamma_5 \psi - \tfrac{1}{2} a_F^{(5)\mu\alpha\beta} F_{\alpha\beta} \overline{\psi}\gamma_\mu \psi - \tfrac{1}{2} b_F^{(5)\mu\alpha\beta} F_{\alpha\beta} \overline{\psi}\gamma_5 \gamma_\mu \psi - \tfrac{1}{4} H_F^{(5)\mu\nu\alpha\beta} F_{\alpha\beta} \overline{\psi}\sigma_{\mu\nu}\psi$$

Thank you for your time ☺