Electric dipole moment: theory for experimentalists on the physics of atomic and nuclear EDMs

Should every physicists be measuring the neutron EDM?
Can the neutron EDM save the world?
Why are so many experiments measuring zero?
Outlook

What is an EDM?
About symmetries
The neutron EDM in the standard model
The strong CP problem and the axion
Beyond the standard model
Widening the picture: other EDMs
Cosmology, dark matter, baryogenesis
Bibliography

The two main books!

CP Violation Without Strangeness by I.B. Khriplovich, and S. Lamoreaux

Discrete Symmetries and CP Violation: From Experiment to Theory by Marco Sozzi
What is an EDM?

\[ \overrightarrow{d_E} = \int \vec{x} \rho(\vec{x}) \, d\vec{x} \]

An EDM originates from an asymmetry in the charge density distribution

\[ H_{\text{int}} = -\overrightarrow{d_E} \cdot \vec{E} \]

Its interaction with an E-field

\[ \overrightarrow{d_E} = q\vec{r} \]

Water molecule
The Wigner-Eckart theorem ...

... getting to quantum physics

For a system in an angular momentum state $|lm>$, and an observable that is a set of $2k + 1$ observables $T^{(k)}_{-k}, T^{(k)}_{-k+1}, \ldots, T^{(k)}_{k}$

the theorem dictates that the expected value of your operator in that state $<lm'|T^{(k)}_k|lm>$ (here with a transition to some other orientation $m'$) split into:

$$<lm'|T^{(k)}_q|lm> = <l|T^{(k)}_l|l><lm'kq>$$

The reduced matrix element, which depends on which representation the state and the observable live in, i.e. on $l$ and $k$ but not on the component $q$ of the observable or on the orientation $m$ of the state.

The Clebsh-Gordan coefficient which encodes all the dependence on the orientation $m$ and $m'$ and of the choice of the observable’s component $q$ but with no knowledge of what $T$ actually is.
The Wigner-Eckart theorem ...

... getting to quantum physics

\[ <lm'|T_q^{(k)}|lm> = <l||T^{(k)}||l> <lm'kq|lm> \]

\[ <\frac{1}{2}m'|v_q|\frac{1}{2}m> = \frac{<\frac{1}{2}||v||\frac{1}{2}> <\frac{1}{2}m'1q|\frac{1}{2}m>}{<\frac{1}{2}||S||\frac{1}{2}> <\frac{1}{2}m'|S|\frac{1}{2}m>} \]

Now, let’s specialize this to some vector operator \( v \), like an EDM and for a spin \( \frac{1}{2} \) particle...

... and to the angular momentum

\[ <\frac{1}{2}m'|v_q|\frac{1}{2}m> = \frac{<\frac{1}{2}||v||\frac{1}{2}>}{<\frac{1}{2}||S||\frac{1}{2}>} \]

Our vector operator is pretty much indistinguishable from the spin

Multiplying by the basis vector \( \vec{e}_q \), and summing over \( q \):

\[ \tilde{v} = \frac{<\frac{1}{2}||v||\frac{1}{2}>}{<\frac{1}{2}||S||\frac{1}{2}>} \hat{S} \]
Symmetries

Noether’s theorem: for every continuous symmetry a corresponding conservation law exists: there is a conserved observable which is a constant of the motion

→ The translation symmetry is the impossibility of determining the absolute position in space for an isolated system and leads to the conservation of momentum

→ The theorem says noting about discrete symmetries which therefore do not lead to conserved quantities

For discrete transformations particular ones are inversions: they are the transformations which give back the same physical system when applied twice
**Parity**

\[ \vec{x} \to \vec{x}_P = -\vec{x} \quad \text{Inversion of the spatial coordinates with respect to the origin} \]

Mirror reflection with respect to an arbitrary plane followed by a \( \pi \) rotation with respect to an axis orthogonal to this plane

\[ \vec{B} \to \vec{B}_P = \vec{B} \quad \text{Axial vector} \]
\[ \vec{E} \to \vec{E}_P = -\vec{E} \quad \text{Polar vector} \]
\[ \vec{S} \to \vec{S}_P = \vec{S} \quad \text{By definition, in analogy with the orbital momentum} \]

\[ H = - (\vec{\mu} \vec{B} + \vec{d} \cdot \vec{E}) \]
\[ PH = - (\vec{\mu} \vec{B} + \vec{d} \cdot (-\vec{E})) \neq H \]
Charge conjugation

Charge conjugation: all charges change sign while all other quantities are unaffected
Particle $\rightarrow$ Antiparticle
Time reversal

Inversion of the time coordinate

Laws of classical physics are invariant under the inversion of time coordinate

Paradox?

In our macroscopic world the arrow of time is obvious

Macroscopic processes is the sum of many elementary interactions

\[
\begin{align*}
\dot{x} &\rightarrow \overrightarrow{x}_T = \ddot{x} \\
\vec{P} &\rightarrow \overrightarrow{P}_T = -\vec{P} \\
\dot{S} &\rightarrow \overrightarrow{S}_T = -\dot{S} \\
\vec{E} &\rightarrow \overrightarrow{E}_T = \vec{E} \\
\vec{B} &\rightarrow \overrightarrow{B}_T = -\vec{B}
\end{align*}
\]

E-field is created by static charges, B-field by moving charges

\[
H = - (\vec{\mu} \cdot \vec{B} + \vec{\alpha} \cdot \vec{E})
\]

\[
TH = - (\vec{\mu} \cdot (B_T) + \vec{\alpha} \cdot (E_T)) \neq H
\]
CPT theorem

Rigorous proof is based on Lorentz invariance and locality

2D space (even space dimension)  Rotation \(\rightarrow\) Reflection of all axis (P)
4D space time  Rotation \(\rightarrow\) PT ?

Vector current \( j_\mu = (\rho, j) \overset{P}{\rightarrow} (\rho, -j) \overset{T}{\rightarrow} (\rho, j) \)  Our space time is pseudo-euclidean

Changing the sign of an energy \(\rightarrow\) particle/antiparticle

4D space time  Rotation \(\rightarrow\) CPT

Vector current \( j_\mu = (\rho, j) \overset{P}{\rightarrow} (\rho, -j) \overset{T}{\rightarrow} (\rho, j) \overset{C}{\rightarrow} (-\rho, -j) \)

Consequences of the CPT theorem:
* If one of the C, P, T symmetries is violated then at least another one must be violated \(T \leftrightarrow CP\)
* Antiparticles must exist even if C is not an exact symmetry of Nature
* Particles and antiparticles have equal masses and lifetimes
* Electromagnetic properties of particles and antiparticles are equal and opposite
* ….. (cross sections, ….)
Symmetry summary

We have this quantity, that is breaking P, T and CP symmetries.

What is it interesting for?
An history of motivations for measuring the nEDM

« I do not believe there is any need for physical laws to be invariant under this reflections*, although all the exact laws of nature so far known do have this invariance »

* reflection in space and time

What is the experimental evidence for the absence of nuclear EDMs (forbidden by parity conservation)?
An history of motivations for measuring the nEDM

From a puzzle …

\[ \Theta^+ \rightarrow \pi^+ + \pi^0 \]
\[ \Gamma^+ \rightarrow \pi^+ + \pi^+ + \pi^- \]
\[ K^+ \]

\( P=+1 \)
\( P=-1 \)

… to parity violation: 1956

Tsung Dao Lee and Chen Ning Yang

[Graph showing CP asymmetry]

1964 CP violation is discovered in the \( K^0 \) decay

CP violation in ordinary (without strangeness, charm, beauty ...) matter: the neutron EDM

Chien-Shiung Wu
The neutron EDM in the standard model and beyond

Adrian SIGNER

I will discuss why we theorists always knew that you wouldn't find a non-vanishing nEDM. Just in case you will measure one, it will also be discussed, why we theorists always knew that you would eventually find a non-vanishing nEDM.

"To be honest, I never would have invented the wheel if not for Urg's groundbreaking theoretical work with the circle."
CP violation in the standard model: the weak sector

The only source of CP violation in the standard model is the phase in the CKM matrix

\[
\begin{pmatrix}
    d' \\
    s' \\
    b'
\end{pmatrix} =
\begin{pmatrix}
    c_{12}c_{13} & i\delta & s_{12}c_{13} \\
    -s_{12}c_{23} - c_{12}s_{23}s_{13} & 1 & c_{12}c_{23} - s_{12}s_{23}s_{13} \\
    s_{12}s_{23} - c_{12}c_{23}s_{13} & i\delta & -c_{12}s_{23} - s_{12}c_{23}s_{13}
\end{pmatrix}
\begin{pmatrix}
    d \\
    s \\
    b
\end{pmatrix}
\]

* The CKM matrix has a hierarchical structure in which each up type quark preferably couples to the down quark of the same family

\[
\begin{pmatrix}
    1 - \frac{1}{2} \lambda^2 & \lambda & \lambda \lambda^3 (\rho - i\eta) \\
    -\lambda & 1 - \frac{1}{2} \lambda^2 & \lambda \lambda^3 \\
    \lambda \lambda^3 (1 - \rho - i\eta) & -\lambda \lambda^3 & 1
\end{pmatrix}
+ O(\lambda^4)
\]

* $\frac{\eta}{\rho} \approx 1$ shows that CP is not even an approximate symmetry of the SM: the smallness of CP violating effect is just due to the small mixing angle.

* One loop level (single boson exchange), no change in quark flavor, each CKM matrix element is accompanied by its complex conjugate; no T-violating complex phase can arise

* Two loop level, individual diagrams have complex phases and contribute to the EDM. However, the sum over all quark flavors in the intermediate states leads to the accidental vanishing of the EDM

* The fact that the quark EDM appears only at the three loop level in the standard model greatly complicates theoretical estimates. The largest effect is due to the exchange of two W bosons and one gluon

\[
d_d = -0.7 \times 10^{-34} \text{ e cm}
\]
\[
d_u = -0.15 \times 10^{-34} \text{ e cm}
\]
CP violation in the standard model: the weak sector

The neutron EDM (from quarks’ EDM)

Naive (valence) approach:

\[ d_n = \frac{4}{3} d_d - \frac{1}{3} d_u \leq 10^{-34} \text{e.cm} \]

The neutron EDM (from “long” distance effect)

The largest Standard Model contribution to \( d_n \) comes not from quark EDMs, but from a four-quark operator generated by a so-called “strong penguin” diagram. This is enhanced by long distance effects, namely the pion loop, and it has been estimated that this mechanism

\[ d_n \approx 10^{-32} \text{e.cm} \]

The neutron EDM is essentially free of SM background!
The strong CP problem and the axion

\[ L_{\text{eff}} = L_{QCD} + \theta \frac{\alpha_S}{8\pi} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma} \]

From lattice calculations: \( d_n = -0.0039(2)(9) \theta \text{ e.f.m}^* \)

Experimental upper limit: \( |d_n| \leq 3.10^{-13} \text{ e.f.m} \)

\( \theta \leq 10^{-10} \)

The strong CP problem
- One mass quark is exactly zero but PDG: \( m_u = 2.2^{+0.6}_{-0.4} \text{ MeV} \)
- Introducing a global chiral U(1) symmetry

This symmetry is necessarily spontaneously broken, and its introduction into the theory effectively replaces the static CP-violating angle \( \theta \) with a dynamical CP-conserving field - the axion. The axion is the Nambu-Goldstone boson of the broken U(1) symmetry.
Axion detour

The axion is a well motivated dark matter candidate
Axion density relative to the critical density of the universe

\[ \Omega_a \approx \left( \frac{6 \, \mu eV}{m_a} \right)^{7/6} \approx \Omega_m = 0.23 \ (m_a \approx 20 \, \mu eV) \]

Entire dark matter density

The theory is quite predictive
Essentially all of the physics of the axion depends on a large unknown energy scale \( f_a \), at which Peccei-Quinn symmetry is broken.

The axion has a two photons coupling, and \( g_\gamma \) is model dependant.

\[ m_a \approx 6 \, eV \left( \frac{10^6 \, GeV}{f_a} \right) \]

\[ g_{a\gamma\gamma} = \frac{\alpha g_\gamma}{\pi f_a} \]
Axion detour

From Irastorza, Redondo, 1801.08127

ALPs Axion Like Particles (Ask Less (just) Probe)
Axion’s circle

Limit on the nEDM

Symmetry breaking

Axion + ALPs

Oscillating nEDM

Kent Leung

Beatrice Franke

Beatrice Franke
The abundances of the light elements depend almost solely on the baryon-to-photon ratio. D/H measurements* + nucleosynthesis models:

$$5.8 \times 10^{-10} < \eta < 6.6 \times 10^{-10}$$

The Planck result**: fraction of cosmological density contained in baryons:

$$\eta = 6.09 (6) \times 10^{-10}$$

*Universe 3, 44 (2017)

Matter/Antimatter Asymmetry of the Universe

\[ \eta = \frac{n_B - n_{\overline{B}}}{n_\gamma} \]

1. You prepare the system in thermal equilibrium with

\[ A_{BB} = \frac{N_B - N_{\overline{B}}}{N_B + N_{\overline{B}}} \approx 0 \]

2. Baryogenesis happens.

3. You find the system in thermal with

\[ A_{BB} = \frac{N_B - N_{\overline{B}}}{N_B + N_{\overline{B}}} \approx 1, \eta \approx 0 \]

Can we say anything general about what happens in Step 2?
How this asymmetry can be explained with particle physics?

→ **Sakharov criteria for baryogenesis**

1) **There must exist an interaction that violates B-number.**
   → You must be able to convert anti-matter into matter or vice versa.
   → We need to pass from a state with $\langle B \rangle = 0$ to a state with $\langle B \rangle > 0$.
   Thus, B cannot be conserved!
Matter/Antimatter Asymmetry of the Universe

How this asymmetry can be explained with particle physics?

*Sakharov criteria for baryogenesis*

1) There must exist an interaction that violates B-number.

2) The B-violating interaction must go out of thermal equilibrium.

→ Suppose the interactions violate B. Now the system can move back-and-forth between states of different B.
→ While the system is in thermal equilibrium, the probability to be found in a given state only depends on the energy of that state. If the theory is invariant under CPT, then particles and anti-particles have the same mass. Then, a state with B=+1 is just as probable as a state with B=-1.
→ The system will oscillate back and forth.
→ To prevent this eternal flip-flop, there must be a time at which the B-violating interaction goes out of thermal equilibrium
Matter/Antimatter Asymmetry of the Universe

How this asymmetry can be explained with particle physics?

→ **Sakharov criteria for baryogenesis**

1) **There must exist an interaction that violates B-number.**

2) **The B-violating interaction must go out of thermal equilibrium.**

3) **There must be an interaction that violates C & CP.**

   → You must bias the production of matter over antimatter.

   → C & CP are symmetries that relate particles to their anti-particle partners.

   → If C & CP are unbroken, a antimatter-creating process will compete with the matter-creating process, and there will be no net effect.
Matter/Antimatter Asymmetry of the Universe

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→ If C & CP are unbroken, a antimatter-creating process will compete with the matter-creating process, and there will be no net effect.

Standard Model

1) OK (Sphalerons)

2) Not OK (Requires Higgs mass < 80meV)

3) Not OK (CKM)
Beyond the standard model

SM→“only” an effective theory valid up to some scale $\Lambda$

$$L_{BSM}$$

First CP violating operators @ DIM6

$$L_{eff} = L_{SM} + \frac{C^{(5)}}{\Lambda} \, \sigma^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} \, \sigma_i^{(6)}$$

Information about the underlying physics

$$d_n = d_{n}^{CKM} + 10^{-16} \, e \cdot cm \, (\theta) + 10^{-24} \, e \cdot cm \left( \frac{200 \, GeV}{M} \right)^2 \sin(\varphi_{CP})$$

nEDM is sensitive to new physics at the multi-TeV scale.

Hadronic / nuclear matrix elements not very well known: strongly dilute the constraining power of the measurements

(dixit Vincenzo Cirigliano:
https://indico.ill.fr/indico/event/87/timetable/#20180525.detailed)
Beyond the standard model

Constraint on non-standard CPV Higgs couplings
Higgs production at LHC
VS
EDMs


Picture by V. Cirigliano (PPNS2018)
Beyond the standard model

Supersymmetry:
Motivated by its ability to solve the hierarchy between the weak scale and the Planck scale
Predicts a superpartner for each particle
Has to be a broken symmetry: in particular, for most scenarios the masses of the superpartners of the first generation quarks (up and down squarks) must be well above a TeV (The LHC has yet to discover any new electroweak scale physics)

Involves new parameters including new CP-violating phases
Beyond the standard model

Fig. 2 Constraints on the (constrained) MSSM phases $\theta_A$ and $\theta_\mu$ from the combined EDM limits (intersection of the bands), using two generic SUSY mass scales and $\tan \beta = 3$ for illustration. On the left, $M_{\text{SUSY}} = 500$ GeV which is now excluded by the LHC, and on the right $M_{\text{SUSY}} = 2$ TeV.

Hyperfine Interactions, 214, 87–95 (2013)
More EDMs

Probing a theory

Single source hypothesis

Neutrons

Nuclei: p, d, $^3$He

Diamagnetic atoms: Hg, Xe, Ra

Paramagnetic atoms: Tl, Cs

Molecules: YbF, PbO, HfF$^+$

Leptons

Schiff moment

atomic theory

nuclear theory

QCD

quark EDM

quark chromo-EDM

lepton EDM

Fundamental theory
\[ |d_{Hg}| < 7.4 \times 10^{-30} e \cdot cm \text{ (95\% C.L.)} \]

TABLE III. Limits on CP-violating observables from the $^{199}\text{Hg}$ EDM limit. Each limit is based on the assumption that it is the sole contribution to the atomic EDM. In principle, the result for $d_n$ supercedes [11] as the best neutron EDM limit.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Expression</th>
<th>Limit</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_n$</td>
<td>$S_{Hg}/(1.9 \text{ fm}^2)$</td>
<td>$1.6 \times 10^{-26} e \cdot cm$</td>
<td>[21]</td>
</tr>
<tr>
<td>$d_p$</td>
<td>$1.3 \times S_{Hg}/(0.2 \text{ fm}^2)$</td>
<td>$2.0 \times 10^{-28} e \cdot cm$</td>
<td>[21]</td>
</tr>
<tr>
<td>$\tilde{g}_0$</td>
<td>$S_{Hg}/(0.135 e \cdot \text{ fm}^3)$</td>
<td>$2.3 \times 10^{-12}$</td>
<td>[5]</td>
</tr>
<tr>
<td>$\tilde{g}_1$</td>
<td>$S_{Hg}/(0.27 e \cdot \text{ fm}^3)$</td>
<td>$1.1 \times 10^{-12}$</td>
<td>[5]</td>
</tr>
<tr>
<td>$\tilde{g}_2$</td>
<td>$S_{Hg}/(0.27 e \cdot \text{ fm}^3)$</td>
<td>$1.1 \times 10^{-12}$</td>
<td>[5]</td>
</tr>
<tr>
<td>$\tilde{g}_{QCD}$</td>
<td>$\tilde{g}_0/0.0155$</td>
<td>$1.5 \times 10^{-10}$</td>
<td>[22, 23]</td>
</tr>
<tr>
<td>$(\tilde{d}_u - \tilde{d}_d)$</td>
<td>$\tilde{g}_1/(2 \times 10^{14} \text{ cm}^{-1})$</td>
<td>$5.7 \times 10^{-27} \text{ cm}$</td>
<td>[25]</td>
</tr>
<tr>
<td>$C_S$</td>
<td>$d_{Hg}/(5.9 \times 10^{-22} e \cdot \text{ cm})$</td>
<td>$1.3 \times 10^{-8}$</td>
<td>[15]</td>
</tr>
<tr>
<td>$C_P$</td>
<td>$d_{Hg}/(6.0 \times 10^{-23} e \cdot \text{ cm})$</td>
<td>$1.2 \times 10^{-7}$</td>
<td>[15]</td>
</tr>
<tr>
<td>$C_T$</td>
<td>$d_{Hg}/(4.89 \times 10^{-20} e \cdot \text{ cm})$</td>
<td>$1.5 \times 10^{-10}$</td>
<td>see text</td>
</tr>
</tbody>
</table>
EDM of atoms

P, T – violating electron-nucleon interaction

Electron EDM
Electron

Proton

Neutron

Nucleon EDM

P, T – violating nucleon- nucleon interaction

Nuclei
Electric Dipole Moments: A Global Analysis

By Timothy Chupp and Michael Ramsey-Musolf

EDMs from a model-independent perspective that does not impose the “single-source” restriction

<table>
<thead>
<tr>
<th>Parameter (units)</th>
<th>95% limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_e$ (e-cm)</td>
<td>$5.4 \times 10^{-27}$</td>
</tr>
<tr>
<td>$C_S$</td>
<td>$4.5 \times 10^{-7}$</td>
</tr>
<tr>
<td>$C_T$</td>
<td>$2 \times 10^{-6}$</td>
</tr>
<tr>
<td>$d_n$ (e-cm)</td>
<td>$12 \times 10^{-23}$</td>
</tr>
<tr>
<td>$g_\pi^{(0)}$</td>
<td>$8 \times 10^{-9}$</td>
</tr>
<tr>
<td>$g_\pi^{(1)}$</td>
<td>$1 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

- e EDM
- T&P-odd Pseudoscalar electron-nucleon interaction
- T&P-odd Tensor electron-nucleon interaction
- “short distance” contribution to the neutron EDM
- T-odd & P-odd Isoscalar pion-nucleon coupling
- T-odd & P-odd Isovector pion-nucleon coupling
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<th>95% limit</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$d_e$ (e-cm)</td>
<td>$5.4 \times 10^{-27}$</td>
<td>Paramagnetic atoms</td>
</tr>
<tr>
<td>$C_S$</td>
<td>$4.5 \times 10^{-7}$</td>
<td>Paramagnetic atoms</td>
</tr>
<tr>
<td>$C_T$</td>
<td>$2 \times 10^{-6}$</td>
<td>Diamagnetic atoms</td>
</tr>
<tr>
<td>$d_n$ (e-cm)</td>
<td>$12 \times 10^{-23}$</td>
<td>Neutron</td>
</tr>
<tr>
<td>$g^{(0)}_\pi$</td>
<td>$8 \times 10^{-9}$</td>
<td>Neutron and Diamagnetic atoms</td>
</tr>
<tr>
<td>$g^{(1)}_\pi$</td>
<td>$1 \times 10^{-9}$</td>
<td>Diamagnetic atoms</td>
</tr>
</tbody>
</table>

Limited by nuclear theory uncertainty (from $^{199}$Hg)
EDM of atoms

Schiff Theorem
* Neutral atomic system of point particles in Electric field readjusts itself to give zero E field at all charges

* BUT relativistic effects and finite size of nucleus can break the symmetry

<table>
<thead>
<tr>
<th>Atom</th>
<th>Z</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li</td>
<td>3</td>
<td>0.004</td>
</tr>
<tr>
<td>Na</td>
<td>11</td>
<td>0.439</td>
</tr>
<tr>
<td>K</td>
<td>19</td>
<td>3.588</td>
</tr>
<tr>
<td>Rb</td>
<td>37</td>
<td>33.732</td>
</tr>
<tr>
<td>Cs</td>
<td>55</td>
<td>154.657</td>
</tr>
</tbody>
</table>

Magnetic enhancement for $d_e$ in paramagnetic atoms $d_{Tl} \approx -585 \, d_e$
EDM of atoms

Deformed nuclei
* Enhanced signal

Intrinsic Schiff moment

\[ S \approx eZ R_0 \frac{9}{20\pi \sqrt{35}} \beta_2/\beta_3 \]

T-P odd interaction \( \rightarrow \) coupling of the 2 states of opposite parity

\[ \Psi^- = (|+\rangle - |-\rangle)/\sqrt{2} \]

\[ \Delta E = (|+\rangle - |-\rangle)/\sqrt{2} \]

\[ \Psi^+ = (|+\rangle + |-\rangle)/\sqrt{2} \]

Electroweak baryogenesis

How this asymmetry can be explained with particle physics?

→ Sakharov criteria for baryogenesis

1) There must exist an interaction that violates B-number.

2) The B-violating interaction must go out of thermal equilibrium.

3) There must be an interaction that violates C & CP.

<table>
<thead>
<tr>
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<th>Before Electroweak phase transition</th>
<th>After Electroweak phase transition</th>
<th>Today</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{N_B - N_B^-}{N_B + N_B^-}$</td>
<td>0</td>
<td>$10^{-10}$</td>
<td>1</td>
</tr>
<tr>
<td>$\frac{N_B}{N_Y}$</td>
<td>$1/2$</td>
<td>$1/2$</td>
<td>$10^{-10}$</td>
</tr>
</tbody>
</table>

1) OK (Sphalerons)

2) Baryogenesis at the weak scale (accessible to EDMs and LHC)

3) New source of CP violation
Electroweak baryogenesis

Exemple in SUSY

New CP violating phases contributes to
* baryonic asymmetry of the universe
* neutron EDM

The nEDM is the most stringent test of electroweak baryogenesis

Another possibility is the leptogenesis where the new source of CP violation is in the lepton sector

Picture by V. Cirigliano
The neutron EDM

* Probe the Electroweak baryogenesis
* Probe physics beyond the standard model at the multi-TeV scale
  One might stop measuring zero!

* Measuring different EDMs will probe the source of CP violation

MERCI
The role of neutron
Beyond the standard model

\[ L_{BSM} = L_{SM} + \frac{C^{(5)}}{\Lambda} \phi^{(5)} + \sum_{i} \frac{C^{(6)}_{i}}{\Lambda^2} \phi^{(6)}_{i} \]

First CP violating operators @ DIM6

\[ d_n = d_n^{CKM} + 10^{-16} \text{ e.cm} (\theta) + 10^{-24} \text{ e.cm} \left( \frac{200 \text{ GeV}}{M} \right)^2 \sin(\phi_{CP}) \]

Information about the underlying physics

nEDM is sensitive to new physics at the multi-TeV scale.
Merci
(i) The EDMs of paramagnetic systems are primarily sensitive to the d e and C S. 
(ii) Diamagnetic atom EDMs carry the strongest sensitivity to C T and the g \( \cdot \) \( \cdot \) \( \pi \), whereas the neutron EDM depends most strongly on d \( \cdot \) \( \cdot \) \( \pi \) and g \( \cdot \) \( \cdot \) \( \pi \) providing four effective CPV parameters that are constrained by results from four experimental systems.
(iii) Inclusion of both d e and C S in the global fit yields an upper bound on each parameter that is an order of magnitude less stringent than would be obtained under the “single-source” assumption.
(iv) Uncertainties in the nuclear theory preclude extraction of a significant limit on g \( \cdot \) \( \cdot \) \( \pi \) from d A (199 Hg), whereas the situation regarding g \( \cdot \) \( \cdot \) \( \pi \) is under better theoretical control. Including the TIF and 129 Xe in the global fit leads to an order of magnitude tighter constraint on g \( \cdot \) \( \cdot \) \( \pi \) than on g \( \cdot \) \( \cdot \) \( \pi \).
(v) Looking to the future, a new probe of the Fr EDM with a d e sensitivity of 10 \( -28 \) e-cm [14] could have a significantly stronger impact on the combined d e -C S global fit than would an order of magnitude improvement in the ThO sensitivity. The addition of new, more stringent limits on the EDMs of the neutron, 129 Xe atom, and 225 Ra atom would lead to substantial improvements in the sensitivities to both g \( \cdot \) \( \cdot \) \( \pi \) and g \( \cdot \) \( \cdot \) \( \pi \).

<table>
<thead>
<tr>
<th>Parameter (units)</th>
<th>95% limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>d_e (e-cm)</td>
<td>5.4 \times 10^{-27}</td>
</tr>
<tr>
<td>C_S</td>
<td>4.5 \times 10^{-7}</td>
</tr>
<tr>
<td>C_T</td>
<td>2 \times 10^{-6}</td>
</tr>
<tr>
<td>d_n (e-cm)</td>
<td>12 \times 10^{-23}</td>
</tr>
<tr>
<td>g^{(0)}_\pi</td>
<td>8 \times 10^{-9}</td>
</tr>
<tr>
<td>g^{(1)}_\pi</td>
<td>1 \times 10^{-9}</td>
</tr>
</tbody>
</table>
On dimensional grounds (de Rujula et al., Nucl Phys B 357, 311 (1991))

\( \Lambda \) is the CP violating scale

\[
d_d \sim 10^{-3} e^{\frac{m_d(\text{MeV})}{\Lambda(\text{TeV})^2}} \sim 10^{-25} / \Lambda(\text{TeV})^2 \text{ e-cm}
\]

The neutron EDM (from quarks’ EDM)

Naive (valence) approach:

\[
d_n = \frac{4}{3} d_d - \frac{1}{3} d_u \leq 10^{-34} \text{ e.cm}
\]
Matter/Antimatter Asymmetry of the Universe

How this asymmetry can be explained with particle physics?

→ Sakharov criteria for baryogenesis

1) There must exist an interaction that violates B-number.
   → You must be able to convert anti-matter into matter or vice versa.
   → We need to pass from a state with \(<B> = 0\) to a state with \(<B> > 0\).
      Thus, B cannot be conserved!

2) The B-violating interaction must go out of thermal equilibrium.
   → Suppose the interactions violate B. Now the system can move back-
     and-forth between states of different B.
   → While the system is in thermal equilibrium, the probability to be found in
     a given state only depends on the energy of that state. If the theory is
     invariant under CPT, then particles and anti-particles have the same mass.
     Then, a state with B=+1 is just as probable as a state with B=-1.
   → The system will oscillate back and forth.
   → To prevent this eternal flip-flop, there must be a time at which the B-
     violating interaction goes out of thermal equilibrium

3) There must be an interaction that violates C & CP.