EDM of hyperons generated by CP-violated three pseudoscalar meson transition

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Baryon assymetry of the Universe and Sakharov conditions:

- **Baryon number violation**: In a fundamental physical theory, there must exist an elementary process at the level of particles and the vacuum in which the baryon number of particles would not be conserved;
- **Departure from thermal equilibrium**: baryon-number-violating interactions must proceed out of thermal equilibrium, driven by the cosmic expansion.
- **CP- symmetry violation (CPV)**: direct processes leading to the emergence of a non-zero baryon number must proceed somewhat faster than reverse processes in which this number disappears.

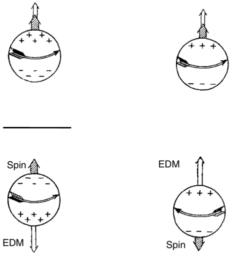
Problem: theoretical estimates demonstrate that the magnitude of CPV provided by the SM turns out to be insufficient to explain the observed baryon asymmetry

Electric Dipole Moment: Definition and Physical Meaning

A non-zero EDM of a spin-1/2 particle is a direct signal of CP violation and a powerful probe of physics beyond the Standard Model.

Definition: For a spin-1/2 particle, the EDM is a separation of the centres of positive and negative charge along the spin direction:

$$\vec{d} = d\,\frac{\vec{S}}{|\vec{S}|}$$



Operation	S (spin, axial)	d (EDM, polar)	d · S (alignment)
P (parity)	$+$	$-$	sign change $\Rightarrow$ **P violated**
T (time reversal)	$-$	$+$	sign change $\Rightarrow$ **T violated**

$\Rightarrow$ A non-zero EDM requires simultaneous violation of P and T, i.e. violation of CP

EM vertex: In the presence of a CP violation, the vertex function splits into form factors

$$\Gamma^\mu = \gamma^\mu F_E + \frac{i\sigma^{\mu\nu} q_\nu}{2m} F_M + \underbrace{\frac{\sigma^{\mu\nu} q_\nu}{2m}\gamma^5 F_D}_{\textbf{EDM}} + \dots$$

Static EDM:

$$d = -\frac{F_D(0)}{2m}$$

SM Context: The only SM source of CP violation is the CKM matrix phase, but it predicts EDMs $\sim 10^{-32}\ e\cdot\text{cm}$ – far below current limits ($\sim 10^{-26}\ e\cdot\text{cm}$) and insufficient for the baryon asymmetry.

- **The θ-term in QCD:** The most general renormalizable QCD Lagrangian includes a topological term:

$$\mathcal{L}_\theta = \bar{\theta}\,\frac{g_s^2}{32\pi^2}\,G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

where $\bar{\theta}$ is a combination of the vacuum angle $\theta_{\mathbf{QCD}}$ and the phase of the quark mass matrix:

$$\bar{\theta} = \theta_{\mathbf{QCD}} + \arg(\det M_q)$$

- **Symmetry Breaking:** This term violates Parity (P) and Time-reversal (T), and consequently CP symmetry (assuming CPT conservation).
- **The Strong CP Problem:**
  - Experimentally, the upper limit on the neutron EDM ($|d_n| < 1.8 \times 10^{-26}\, e \cdot \text{cm}$) constrains it to:

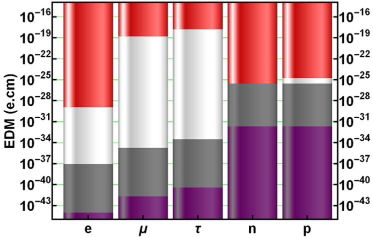
$$|\bar{\theta}| \lesssim 10^{-10}$$

Problem: why is $\bar{\theta}$ so unnaturally small? The SM offers no natural explanation — one of the deepest puzzles of particle physics.

Proposed Solutions

- **Peccei–Quinn Mechanism:** global $U(1)_{PQ}$ broken spontaneously $\Rightarrow$ axion dynamically relaxes $\bar{\theta} \to 0$ (most favoured).
- **Massless Up Quark ($m_u = 0$):** makes $\arg\det M_q$ unphysical (disfavoured by lattice QCD).
- **Spontaneous CP/Parity Violation:** CP/Parity broken spontaneously at high scales, suppressing $\bar{\theta}$ naturally (Nelson–Barr, L–R models).

Current Experimental Landscape of EDM Searches



Particle	Method	Upper limit (e·cm C.L. 90%)
electron	ThO	1.1×10^{-29}
muon	(g-2) storage ring	1.5×10^{-19}
tau	eEDM, updated	1.6×10^{-18}
neutron	Hg	1.4×10^{-26}
neutron	UCN storage	1.8×10^{-26}
proton	Hg	1.7×10^{-25}
^{129}Xe	Xe	1.2×10^{-27}
^{199}Hg	Hg	6.3×10^{-30}

Key Observations: Nucleon EDMs

- **Neutron EDM** — best direct limit: $|d_n| < 1.8 \times 10^{-26}$ $e \cdot$ cm (90% C.L.) from ultracold neutrons at PSI [Abel et al., 2020].
- **Proton EDM** — only indirect limit: $|d_p| < 1.7 \times 10^{-25}$ $e \cdot$ cm from ^{199}Hg atomic EDM.

Hyperon EDMs: Experimental Landscape and Motivation

Hyperon	Current Limit	Method
Λ	$\lvert d_\Lambda \rvert < 6.5 \times 10^{-19}\ e \cdot \mathrm{cm}$	$J/\psi \to \Lambda\bar{\Lambda}$ (BESIII)
Λ (1981)	$\lvert d_\Lambda \rvert < 1.25 \times 10^{-16}\ e \cdot \mathrm{cm}$	Spin precession (Fermilab)
Σ^+	—	—
Ξ^-	—	—
Ξ^0	—	—

Why Study Hyperon EDMs?

- **Strange quark sensitivity:** Λ, Σ (one s), Ξ (two s) probe s-quark CPV, complementary to neutron (u, d).
- **BSM scenarios:** Enhanced strange CPV possible in SUSY, leptoquarks, left-right models $\Rightarrow$ potentially large hyperon EDMs.
- **Disentangling sources:** Joint fit of d_n, d_Λ, d_Ξ can separate quark EDM, chromo-EDM, and $\bar{\theta}$-term.
- **Chiral dynamics:** In χPT, $\bar{\theta}$ induces CP-violating **three-meson vertices** ($\eta\pi\pi$, $K\pi\pi$, etc.) that generate hyperon EDMs at two-loop level $\to$ a possible relationship between θ and the observables.
- **Unexplored territory:** Ξ EDM never measured; STCF sensitivity $\sim 10^{-19}$–$10^{-21}\ e \cdot \mathrm{cm}$.
- **Novel method:** Entangled $B\bar{B}$ pairs from J/ψ decay — no spin precession needed for short-lived hyperons.

Key Achievement now: BESIII improved Λ EDM limit by **3 orders of magnitude** (2025) using 10^{10} J/ψ events.

General structure :

$$\mathcal{L}_\chi = \mathcal{L}^{(2)}_{\phi\phi} + \mathcal{L}^{(1)}_{\phi B} + \dots$$

1. Meson Lagrangian: $\mathcal{L}^{(2)}_{\phi\phi}$ $\qquad (U = e^{i\sqrt{2}\phi/F_0},\ F_0 \approx 92\,\text{MeV})$

$$\mathcal{L}^{(2)}_{\phi\phi} = \frac{F_0^2}{4}\,\text{Tr}\left[D_\mu U (D^\mu U)^\dagger + \chi U^\dagger + U\chi^\dagger\right],$$

- $D_\mu U = \partial_\mu U - ieA_\mu[Q, U]$, $\quad Q = \text{diag}(2/3, -1/3, -1/3)$: photon coupling.
- $\chi = 2BM_q$, $M_q = \text{diag}(m_u, m_d, m_s)$, $B \simeq 2.8\,\text{GeV}$: explicit chiral breaking.

2. Meson–baryon Lagrangian $\mathcal{L}^{(1)}_{\phi B}$ (axial-vector coupling, $\mathcal{O}(p)$)

$$\mathcal{L}^{(1)}_{\phi B} = \text{Tr}\left[\bar{B}(i\hat{D} - m_0)B\right] - \frac{D}{2}\,\text{Tr}\left[\bar{B}\gamma^\mu\gamma_5\{u_\mu, B\}\right] - \frac{F}{2}\,\text{Tr}\left[\bar{B}\gamma^\mu\gamma_5[u_\mu, B]\right],$$

- $u_\mu = i[u^\dagger(\partial_\mu - ieA_\mu Q)u - u(\partial_\mu - ieA_\mu Q)u^\dagger]$, $\quad u = \sqrt{U}$.
- $D \approx 0.80$, $F \approx 0.46$ (from hyperon β-decays), $D + F = g_A = 1.27$.

Meson–Baryon Interaction: PV and PS Formulations

Pseudovector (PV) coupling $(u_\mu = i[u^\dagger(\partial_\mu - iv_\mu)u - u(\partial_\mu - iv_\mu)u^\dagger])$

- Linear expansion $u_\mu \simeq -\partial_\mu \varphi / F_0$ gives derivative interaction:

$$\mathcal{L}^{\mathrm{PV}}_{\phi BB} = \frac{i}{F_0}\left(d_{abc} D + i f_{abc} F\right) \bar{B}_b \gamma^\mu \gamma^5 B_a \, \partial_\mu \varphi_c$$

- d_{abc}, f_{abc} are the symmetric and antisymmetric $SU(3)$ structure constants.

Pseudoscalar (PS) formulation

- Unitary chiral rotation of baryon fields:

$$B \to \exp\Big(-\frac{i\gamma_5\, \vec{\pi}\cdot\vec{\tau}}{2F_\pi}\Big)\, B$$

  leaves the free Lagrangian invariant and removes the derivative from the interaction.
- On the mass shell both formulations give identical matrix elements.
- Using the Dirac equation, the derivative is transferred to the baryon fields:

$$\partial_\mu \left(\bar{B}_b \gamma^\mu \gamma^5 B_a\right) = i(M_b + M_a)\, \bar{B}_b \gamma^5 B_a$$

  which yields an effective non-derivative vertex $\propto (M_a + M_b)\, \bar{B}_b i\gamma_5 B_a \phi_c$.
- **Advantage for EDM calculations:**
  - Minimal substitution $\partial_\mu \to D_\mu$ in PS does not generate additional contact vertices (no Kroll–Ruderman terms).
  - The full set of two-loop diagrams is **ultraviolet finite** without Weinberg–Tomozawa counterterms.

Thus the PS approach provides a computationally transparent and reliable framework for the two-loop hyperon EDM.

CP-Violating Three-Meson Vertex from the $\bar{\theta}$-Term

- QCD Lagrangian admits a gauge-invariant P and T violating topological term:

$$\mathcal{L}_\theta = \bar{\theta}\,\frac{g_s^2}{32\pi^2}\,G^a_{\mu\nu}\tilde{G}^{a\mu\nu}\,, \qquad \bar{\theta} = \theta_{\mathbf{QCD}} + \arg\det M_q$$

- An axial chiral rotation of quark fields makes χ complex: $\chi \to \chi e^{-i\bar{\theta}}$.
- Expanding $U = \exp(i\sqrt{2}\Phi/F_0)$ in $\mathcal{L}^{(2)}_{\phi\phi}$, the imaginary part of the mass term generates CP-violating triple vertices:

$$\mathcal{L}_{CP} = -\frac{\bar{\theta}m_\pi^2}{6F_\pi\bar{m}m^*}\,\frac{m_u m_d}{(m_u+m_d)^2}\,\mathrm{Tr}(\phi^3)$$

where $\bar{m} = \frac{m_u+m_d}{2}$, $m^* = \frac{m_u m_d m_s}{m_s(m_u+m_d)+m_u m_d}$.

- Substituting physical states, the isospin-conserving part dominating the two-loop EDM reads:

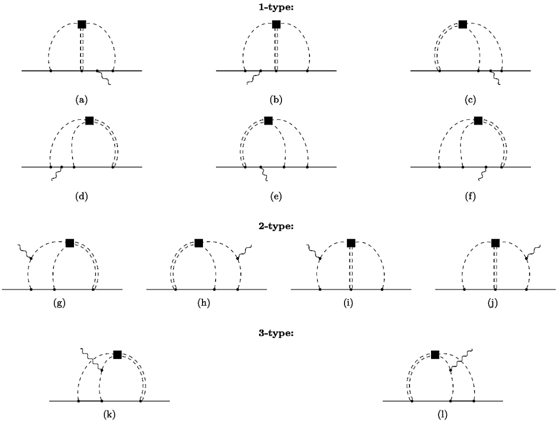
$$\boxed{\mathcal{L}^{\Delta I=0}_{CP} = -\frac{m_\pi^2}{6F_\pi\bar{m}m^*}\,\bar{\theta}\sqrt{3}\left[\eta\vec{\pi}^2 + \sqrt{3}\,K^\dagger\vec{\pi}\cdot\vec{\tau}\,K - \eta K^\dagger K\right]}$$

(Isospin-breaking terms $\propto (m_u - m_d)$ are further suppressed and omitted at leading order.)

- The vertex is proportional to $\bar{\theta}$ and involves three pseudoscalar fields — it drives the generation of baryon EDMs at two loops.

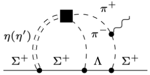
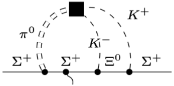
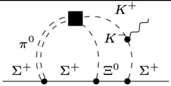
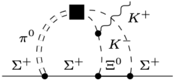
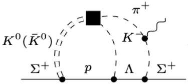
Two-Loop Topologies for Hyperon EDMs

Based on the CP-violating ϕ^3 vertex and the PS meson–baryon couplings, the EDM arises at the two-loop level. Three main topological types of diagrams contribute:



1-type: photon couples to charged baryon inside the loop.
2-type: photon couples to charged meson inside the loop (two routings).
3-type: photon couples to charged meson (alternative routing).

Solid line = baryon, dashed double line = meson, black square = CP-violating ϕ^3 vertex, wavy line = photon.

Channel	Diagram(Leading contribution)
$\eta(\eta')$: $-5.16(-4.67) \cdot 10^{-16}\bar{\theta}e \cdot cm$	
π^0: $1.71 \cdot 10^{-16}\bar{\theta}e \cdot cm$	
π^0: $1.55 \cdot 10^{-16}\bar{\theta}e \cdot cm$	
π^0: $1.22 \cdot 10^{-16}\bar{\theta}e \cdot cm$	
$K^0(\bar{K}^0)$: $8.04 \cdot 10^{-16}\bar{\theta}e \cdot cm$	
Total: $6.76 \cdot 10^{-16}\bar{\theta}e \cdot cm$	

Future Experimental Prospects for EDMs

Hyperon EDMs

Experiment	Status	Method	Hyperons	Expected sensitivity
BESIII	running	Entangled $B\bar{B}$ from J/ψ (angular analysis)	Λ, Σ^+, Ξ^-, Ξ^0	$\lvert d_\Lambda\rvert < 6.5\times10^{-19}$ e·cm; $\Sigma^+ \sim 10^{-19}$, $\Xi \sim 10^{-18}$
STCF	proposed	Same technique, higher luminosity	Λ, Σ^+, Ξ^-, Ξ^0	$10^{-20} - 10^{-21}$ e·cm
LHCb	planned	Bent-crystal spin precession	Ξ^-, $\Sigma^\pm$, Ω^-	complementary (first projections under study)
PANDA (FAIR)	future	$\bar{p}p \to \Xi\bar{\Xi}$, angular analysis	Ξ^-, Ξ^0 (multi-strange)	to be evaluated

Prospects: BESIII already improved Λ EDM limit by 3 orders of magnitude. STCF will open the multi-strange sector (Ξ) and reach sensitivities where many BSM scenarios predict signals. Combination of all hyperon species will disentangle flavour structure of CP violation.

Nucleon and Deuteron EDMs

Experiment	Status	Method	Particle	Expected sensitivity
Storage Ring EDM (BNL)	proposed	Spin precession in electrostatic ring	p, d, ^{3}He	$\sim 10^{-29}$ $e \cdot$cm
JEDI (Jülich)	proposed	Spin precession in magnetic storage ring	p, d	$\sim 10^{-29}$ $e \cdot$cm
nEDM (PSI, SNS, ...)	running	Ultracold neutron storage	n	$\lvert d_n\rvert < 1.8\times10^{-26}$ $e \cdot$cm (curr.) future $\sim 10^{-28}$

Prospects: Proton and deuteron EDMs at 10^{-29} $e \cdot$ cm will tighten the $\bar{\theta}$ bound to $\lvert\bar{\theta}\rvert < 2 \times 10^{-13}$ and could approach sensitivities to SUSY and other BSM CP phases. Joint analysis of n, p, d separates isoscalar and isovector CP-odd couplings, greatly enhancing discovery potential.

Nucleon EDMs

- **Model:** Phenomenological Lagrangian with pseudoscalar (PS) meson-nucleon couplings; CP-violating $\eta^{(\prime)}\pi\pi$ vertices; two-loop diagrams with minimal photon couplings.
- **Neutron EDM**:

$$d_n \approx 0.64 \times 10^{-\mathbf{16}}\,\bar{\theta}\,e\cdot\text{cm} \quad \text{(Zhevlakov et al., PRD 99, 115004)},$$

$$d_n = -(1.5 \pm 0.7) \times 10^{-\mathbf{16}}\,\bar{\theta}\,e\cdot\text{cm} \quad \text{(de Vries et al., arXiv:2001.09050)}.$$

- **Proton EDM**:

$$d_p \approx 0.15 \times 10^{-\mathbf{16}}\,\bar{\theta}\,e\cdot\text{cm} \quad \text{(Zhevlakov et al., PRD 99, 115004)},$$

$$d_p = (1.1 \pm 1.0) \times 10^{-\mathbf{16}}\,\bar{\theta}\,e\cdot\text{cm} \quad \text{(de Vries et al., arXiv:2001.09050)}.$$

- From $|d_n^{\mathbf{exp}}| < 2.9 \times 10^{-\mathbf{26}}\,e\cdot\text{cm} \Rightarrow |\bar{\theta}| < 4.4 \times 10^{-\mathbf{10}}$ (ChPT)

Σ^+ Hyperon EDM

- **Model:** SU(3) ChPT at NLO; LECs fixed by lattice QCD at $M_\pi = 530\,\text{MeV}$.
- Σ^+ EDM:

$$d_{\Sigma^+} = (-0.7 \pm 0.5 \pm 1.0) \times 10^{-\mathbf{16}}\,\bar{\theta}_\mathbf{0}\,e\cdot\text{cm},$$

where $\bar{\theta}_\mathbf{0}$ is the renormalized CP-violating parameter
(Guo & Meißner, JHEP 1212 (2012) 097).