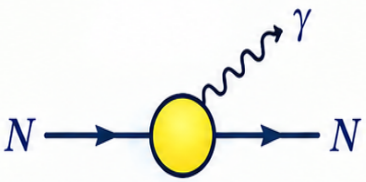
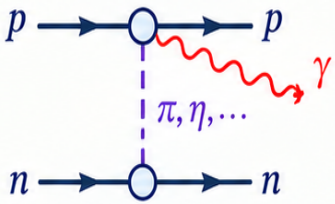
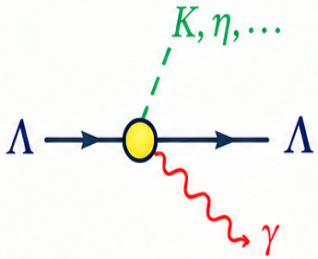
Electric dipole moments of nucleons, deuterons and hyperons induced by CP violating couplings of pseudoscalar mesons.



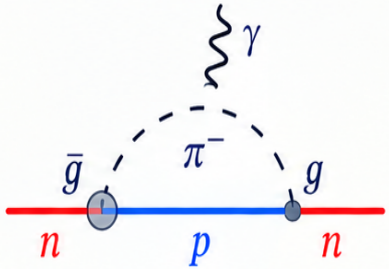
Nucleon EDM



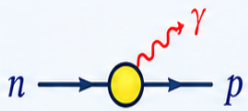
Deuteron EDM



Hyperon EDM



Hadronic Contributions



Deuteron EDM
(via CP-odd πN interaction)

Alexey.S. Zhevlakov

BLTP, JINR

Based on:
A.S.Zh and V.E.Lyubovitskij, Phys.Rev.D 101 (2020) 11, 115041 [arXiv:2003.12217 [hep-ph]].
A.S.Zh, T.Gutsche and V.E.Lyubovitskij, Phys.Rev.D 99 (2019) 11, 115004 [arXiv:1904.08154 [hep-ph]].
A.S.Zh, M.Gorchtein, A.N.Hiller Blin, T.Gutsche and V.E.Lyubovitskij, Phys.Rev.D 99 (2019) 3, 031703 [arXiv: 1812.00171 [hep-ph]].
And one paper in preparation with V.E.Lyubovitskij and E. Oleynik

Outline

- Motivation // EDM status
- EDM of nucleons
- Deuteron EDM
- Hyperons EDM
- Conclusion
- Outlook

Experimental measurements of neutron EDM

- **First Ramsey measurement**

  Smith, Purcell & Ramsey, Phys. Rev. 108, 120 (1957)

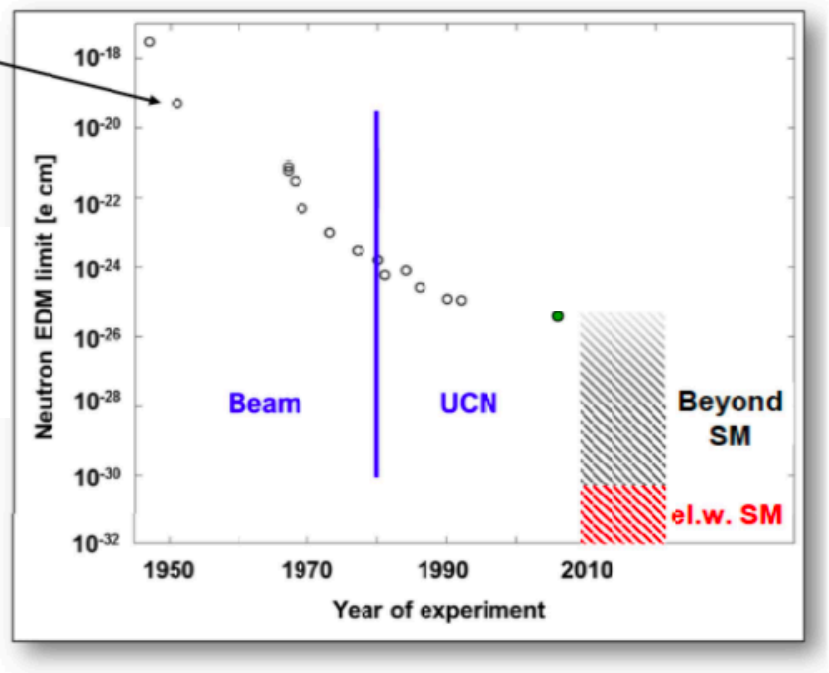
- **Current limit:**

$$d_n < 1.8 \times 10^{-26} e \cdot cm$$

PHYSICAL REVIEW LETTERS 124, 081803 (2020)

- **Sensitivity:**

$$\sigma(d_n) \propto \frac{1}{E\,T\sqrt{N}}$$



Previous data on neutron EDM is limited $< 2.9 \times 10^{-26}\ e \cdot$ cm.
Future experiments are expected to extend the sensitivity to $10^{-27} \div 10^{-29}$ e cm. (PSI, PNPI-ILL-PNPI, LANL Room Temperature EDM experiment, TRIUMF/KEK experiment, SNS experiment, Store Ring EDM and JEDI Collaborations)
Besides, we have a projects for measurements deuteron EDM at NICA and HIAF factory (D.Gou, V. Ladygin, F. Rathmann, A. Silenko, Yu. Uzikov, Natural Sci.Rev. 3 (2026) 200802).

EDM

EDMs have become a major focus of contemporary research for several interconnected reasons:

- EDMs provide a direct experimental probe of CP violation, a feature of the Standard Model (SM) and Beyond-Standard-Model (BSM) physics;
- The P-violating and T-violating EDM signal distinguishes much weaker CP-violating interactions from the dominant strong and electromagnetic interactions;
- CP violation is a required component of the Sakharov's recipe for baryon asymmetry, the fact that there is more matter than antimatter in the Universe, however SM CP- violation cannot produce the observed asymmetry, and new CP violating interactions are required.

arXiv:1710.02504 (T.E. Chupp, P. Fierlinger, M.J. Ramsey-Musolf and J.T. Singh)

CP -violation

The topological charge operator coupled to an external field is added to the QCD Lagrangian:

$$\mathcal{L} = \mathcal{L}_{QCD} - \frac{g^2}{16\pi}\theta(x)\mathrm{Tr}_c(G_{\mu\nu}\tilde{G}^{\mu\nu}) \tag{1}$$

with $\tilde{G}^{\mu\nu}$ is dual tensor to $G^{\mu\nu}$ and Tr_c is the trace over the color indices. Under $U(1)_R \times U(1)_L$ the axial $U(1)$ anomaly adds a term $-\frac{g^2}{16\pi}2N_f\alpha\mathrm{Tr}_c(G_{\mu\nu}\tilde{G}^{\mu\nu}))$ to the QCD Lagrangian, with N_f being the number of different quark flavors and α the angle of the global axial $U(1)$ rotation. The vacuum angle $\theta(x)$ is in this context treated as an external field that transforms under an axial U(1) rotation as

$$\theta(x) \to \theta'(x) = \theta(x) - 2N_f\alpha.$$

The symmetry group $SU(3)_R \times SU(3)_L$ of the Lagrangian $\mathcal{L}_{QCD}$ is extended3 to $U(3)_R \times U(3)_L$ for $\mathcal{L}$. The Green functions of QCD are obtained by expanding the generating functional around $\theta(x) = \theta_0$ where the phase of the quark mass matrix emerging from the Yukawa couplings of the light quarks in the electroweak sector has been absorbed in θ_0. The extended symmetry remains at the level of an effective theory and the additional source θ also shows up in the effective Lagrangian.
B. Borasoy was proposed and made the chiral effective meson and meson baryon actions which dependent onto θ_0 parameter.

Our calculation is based on ChPT with finale with the transition to consideration pseudoscalar type baryon- meson-baryon interaction.

$$\mathcal{L}_{int} = \mathcal{L}^{(2)}_{\phi\phi} + \mathcal{L}^{(1)}_{\phi B} + \mathcal{L}_{CP}, \tag{2}$$

$$\mathcal{L}^{(2)}_{\phi\phi} = \frac{F_0^2}{4}\mathrm{Tr}\left[D_\mu U (D^\mu U)^\dagger + \chi U^\dagger + U\chi^\dagger\right], \tag{3}$$

$$\mathcal{L}^{(1)}_{\phi B} = \mathrm{Tr}\left[\bar{B}(i\hat{D} - m)B\right] - \frac{D}{2}\mathrm{Tr}\left[\bar{B}\gamma^\mu\gamma^5\{u_\mu, B\}\right] - \frac{F}{2}\mathrm{Tr}\left[\bar{B}\gamma^\mu\gamma^5[u_\mu, B]\right], \tag{4}$$

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

The term associated with the explicit breaking of chiral symmetry by quark masses is given through:

$$\chi = 2BM, \quad \chi_+ = u^\dagger\chi u^\dagger + u\chi^\dagger u, \tag{6}$$

where $M = \mathrm{diag}(m_u, m_d, m_s)$ is the current quark mass matrix, $U(x) = \exp\left(i\sqrt{2}\phi/F_0\right)$ is the unitary matrix containing the pseudoscalar meson fields ϕ, and F_0 is the weak pion decay constant in the chiral limit.

The meson mass term $\mathcal{L}_{\text{meson}} \supset (f_\pi^2/2)B_0 \text{tr}[M^\dagger U + U^\dagger M]$ also gives CP violating interaction terms involving mesons. This interaction is come from the quark mass matrix M, which have a form $M = diag(m_u, m_d, m_s) + i\tilde{\theta} m_* I$, We obtain the triple pion coupling to be

$$\mathcal{L}_{3\pi} = \frac{\bar{\theta} B_0 m_*}{3 f_\pi} \pi^a \pi^b \pi^c d_{abc} = \frac{\bar{\theta} m_*}{\bar{m}} \frac{m_\pi^2}{6 f_\pi} \pi^a \pi^b \pi^c d_{abc} \,, \tag{7}$$

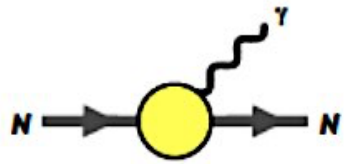
where d^{abc} is defined in terms of the Gell-Mann matrices λ^a which satisfy $\{\lambda^a, \lambda^b\} = (4/3)\delta^{ab} + 2d^{abc}\lambda^c$.

$$\begin{aligned}
\mathcal{L}_{3\pi} = & \frac{\bar{\theta} m_*}{\bar{m}} \frac{m_\pi^2}{\sqrt{3} f_\pi} \left(\eta \pi^+ \pi^- + \frac{1}{2} \eta \pi^0 \pi^0 \right) - \frac{\bar{\theta} m_*}{\bar{m}} \frac{m_\pi^2}{6\sqrt{3} f_\pi} \eta^3 \\
& - \frac{\bar{\theta} m_*}{\bar{m}} \frac{m_\pi^2}{2\sqrt{3} f_\pi} \eta (K^+ K^- + K^0 \bar{K}^0) \\
& + \frac{\bar{\theta} m_*}{\bar{m}} \frac{m_\pi^2}{2 f_\pi} \left(\pi^0 K^+ K^- - \pi^0 K^0 \bar{K}^0 + \sqrt{2} \pi^- K^+ \bar{K}^0 + \sqrt{2} \pi^+ K^- K^0 \right).
\end{aligned} \tag{8}$$

where

$$m_* = 1/(m_u^{-1} + m_d^{-1} + m_s^{-1}).$$
$$\bar{m} = (m_u + m_d)/2$$

EDM of nucleons



Nucleon EDM

The well-known decomposition of the electromagnetic vertex function of baryons in terms of relativistic form factors $F_I(Q^2)$, with $I = E, M, D, A$, reads

$$\bar{N}(p_2)\Gamma(p_1,p_2)N(p_1) = \bar{N}(p_2)\left[\gamma^\mu F_E(Q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2m}F_M(Q^2)\right.$$
$$\left. + \frac{\sigma^{\mu\nu}\gamma_5 q_\nu}{2m}F_D(Q^2) + (\gamma^\mu q^2 - 2mq^\mu)\gamma_5 F_A(Q^2))\right] N(p_1).$$

Here $Q^2 = (p_2 - p_1)^2$, m is the baryon mass, γ^μ, γ_5 are the Dirac matrices, $\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$, $F_E(Q^2), F_M(Q^2), F_D(Q^2)$ and $F_A(Q^2)$ are the electric, magnetic, dipole and anapole form factors of baryons. The electric dipole moment of the neutron is defined as $d_n^E = -F_D(0)/(2m_N)$.

EDM of nucleons // two loop

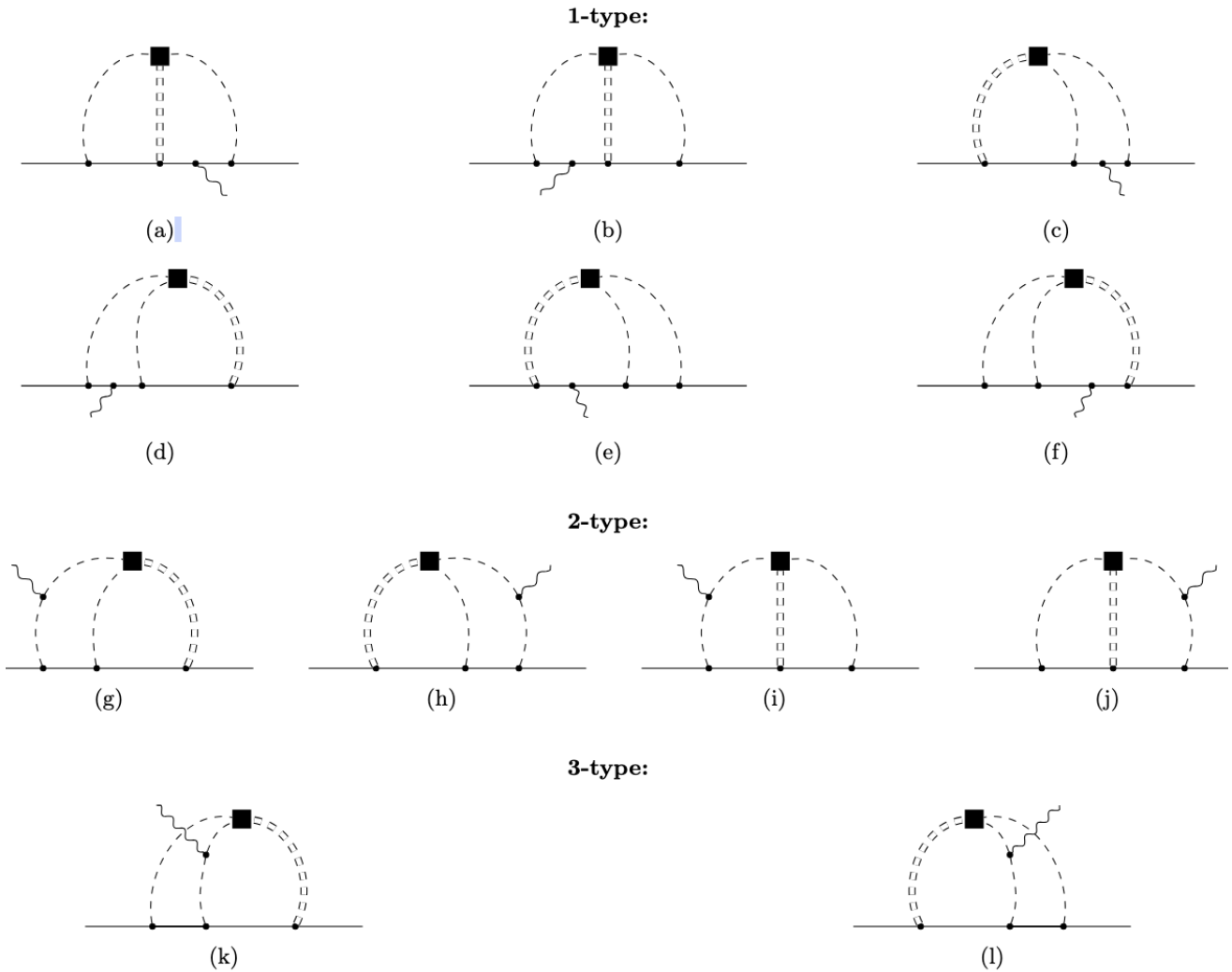


FIG. 1: Types of diagrams

EDM of nucleons

Estimated value of EDM of neutron

$$d_n^E \simeq (6.62 f_{\eta\pi\pi} + 7.64 f_{\eta'\pi\pi}) \times 10^{-16} \mathrm{e} \cdot \mathrm{cm}. \tag{9}$$

in terms of the QCD $\bar{\theta}$ angle:

$$|d_n^E| \simeq 0.64 \times 10^{-16} \bar{\theta}\, \mathrm{e} \cdot \mathrm{cm}\,, \tag{10}$$

using the ratio of u- and $d-$ quarks $R = 0.556$ from ChPT at 1 GeV scale

Estimated value of EDM of proton

$$d_p^E \simeq (1.66 f_{\eta\pi\pi} + 1.77 f_{\eta'\pi\pi}) \times 10^{-16} \mathrm{e} \cdot \mathrm{cm}\,. \tag{11}$$

The pEDM in terms of the $\bar{\theta}$ as:

$$|d_p^E| \simeq 0.15 \times 10^{-16} \bar{\theta}\, \mathrm{e} \cdot \mathrm{cm}\,, \tag{12}$$

for $R = 0.556$ from ChPT

The Schiff moments of nucleons

$$S'_N = -\frac{d_N^E(Q^2)}{dQ^2}\bigg|_{Q^2=0} . \tag{13}$$

Our numerical results for the nucleon SFMs are:

$$|S'_n| < (4.1\, f_{\eta\pi\pi} + 4.4\, f_{\eta'\pi\pi}) \cdot 10^{-3}\, \mathrm{e}\cdot\mathrm{fm}^3\,, \tag{14}$$

$$|S'_p| < (3.7\, f_{\eta\pi\pi} + 3.9\, f_{\eta'\pi\pi}) \cdot 10^{-3}\, \mathrm{e}\cdot\mathrm{fm}^3 \tag{15}$$

in terms of the CP-violating $\eta\pi\pi$ and $\eta'\pi\pi$ couplings and in terms of the QCD vacuum angle

$$|S'_n| < 3.9 \cdot 10^{-4}\, \bar{\theta}\, \mathrm{e}\cdot\mathrm{fm}^3\,, \tag{16}$$

$$|S'_p| < 3.6 \cdot 10^{-4}\, \bar{\theta}\, \mathrm{e}\cdot\mathrm{fm}^3\,, \tag{17}$$

for the ChPT set

EDM of nucleons

In 2025, the BESIII collaboration published the first application of this method to a real dataset, analyzing вЇё 1010 J/ПЇ production events. New Experimental upper limit $|d_\Lambda| < 6.5 \times 10^{-19}\ e \cdot \text{cm}$.

For Hyperons, now calculation in finale stage. For Σ^+ hyperon we obtain:

Estimated value of EDM of neutron

$$|d^E_{\Sigma^+}| \simeq 2.5 \times 10^{-16} \bar{\theta} \text{e} \cdot \text{cm}. \tag{18}$$

in paper Feng-Kun Guo and Ulf-G. Meissner [JHEP12(2012)097]

$$|d^E_{\Sigma^+}| \simeq\simeq (0.7 \pm 0.5 \pm 1.0) \times 10^{-16} \bar{\theta}\, \text{e} \cdot \text{cm}\,, \tag{19}$$

where used lattice for fixed LECs.

The deuteron EDM is sum

Deuteron EDM:

$$d_D^E = d_p^E + d_n^E + d_D^{\pi NN}, \tag{20}$$

where $d_D^{\pi NN}$ is the two-body contribution due to pion meson exchange generated by $\pi^0 - \eta$ and $\pi^0 - \eta'$ mixing.
The two-body contributions can be estimated using potential approach proposed and developed in work of Khriplovich and Korkin (1999). In case of the pion exchange it was shown that the dominant contribution comes due to the isospin triplet coupling

$$d_D^{\pi NN} = -\frac{e g_{\pi NN}\, g_{\pi NN}^{\mathrm{CP}(1)}}{12\pi M_\pi}\, \rho_\pi\,, \tag{21}$$

where

$$\rho_P = \frac{1+\xi_P}{(1+2\xi_P)^2}\,, \quad \xi_P = \frac{\sqrt{m_N \epsilon_D}}{M_P}\,. \tag{22}$$

Here $P = \pi, \eta, \eta'$ and $\epsilon_D = 2.23$ MeV is they, $g_{\pi NN}^{\mathrm{CP}(1)}$ is the CP-violating πNN isospin-breaking coupling constant.

Deuteron EDM // πNN coupling

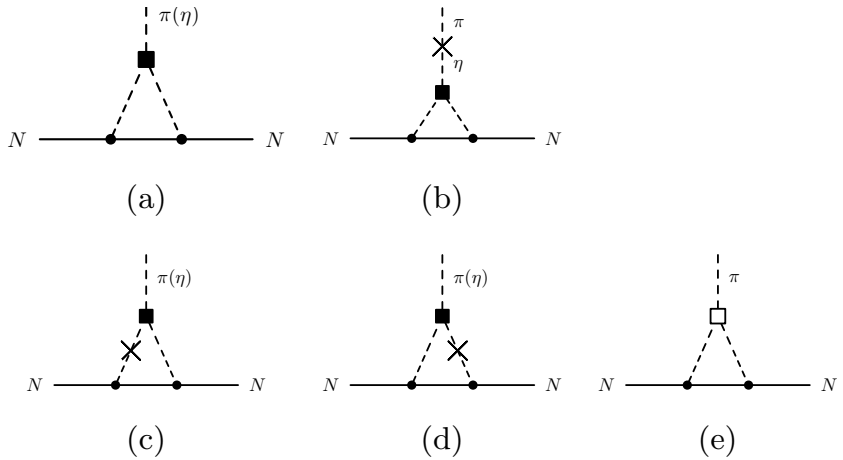


Figure: CP-violating πNN and ηNN couplings: (a) diagram induced by isospin-symmetric ($|\Delta T| = 0$) vertices; (b) and (c) diagrams induced by isospin-violating ($|\Delta T| = 1$) vertices induced by the *internal* $\pi^0 - \eta$ mixing; (d) diagram induced by isospin-violating ($|\Delta T| = 1$) pion-nucleon vertex and by the *external* $\pi^0 - \eta$ mixing. The cross symbol $\times$ denotes the $\pi^0 - \eta$ mixing; (e) diagram induced by CP-violating isospin-breaking coupling of three pseudoscalar mesons from Lagrangian (**??**). The black box symbol denotes the CP-violating isospin-symmetric P^3 vertex. The white box symbol denotes the CP-violating isospin-breaking P^3 vertex.

Deuteron EDM // πNN coupling

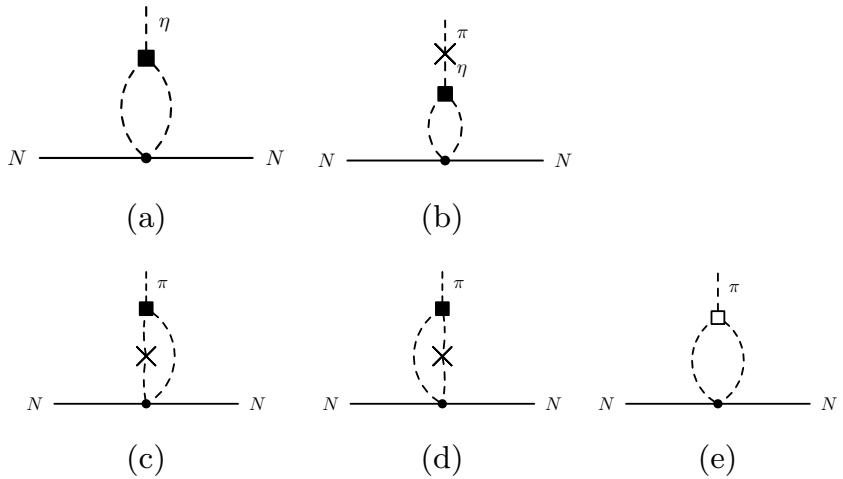
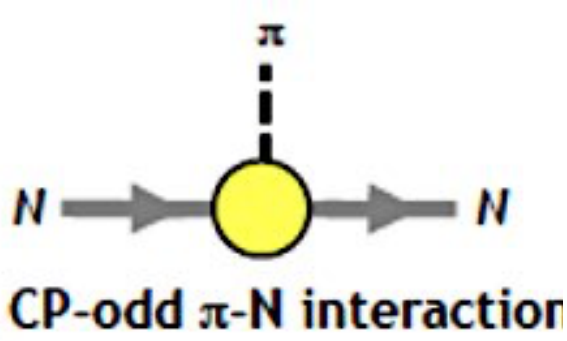


Figure: CP-violating couplings due to seagull term (nonderivative two-meson-two-baryon coupling:: (a) diagram induced by isospin-symmetric ($|\Delta T| = 0$) vertex of ηNN; and diagrams induced by isospin-violating ($|\Delta T| = 1$) πNN CP-violated couplings: (b) and (c) diagrams vertices induced by the *internal* $\pi^0 - \eta$ mixing; (d) diagram induced by isospin-violating ($|\Delta T| = 1$) pion-nucleon vertex and by the *external* $\pi^0 - \eta$ mixing. The cross symbol $\times$ denotes the $\pi^0 - \eta$ mixing; (e) diagram induced by CP-violating isospin-breaking coupling of three pseudoscalar mesons from Lagrangian of CP-violation 3-meson transition. The black box symbol denotes the CP-violating isospin-symmetric P^3 vertex. The white box symbol denotes the CP-violating isospin-breaking P^3 vertex.



The CP-violating HNN, $H = \eta, \eta'$ couplings have been calculated in ChPT in Ref. [**?**]. It is defined by pion-loop diagram and its value at the leading order in chiral expansion reads:

$$g^{\rm CP}_{HNN} = -\frac{3g_A^2 f_{H\pi\pi}}{16\pi^2 F_\pi^2}\ M_H\, m_N = -\frac{3\, g^2_{\pi NN}\, \tilde{f}_{H\pi\pi}}{16\pi^2}\,, \tag{23}$$

which corresponds to the tree-level contribution in the SU(3) baryon ChPT

[**T. Gutsche, A. N. Hiller Blin, S. Kovalenko, S. Kuleshov, V. E. Lyubovitskij, M. J. Vicente Vacas and A. S. Zh., Phys.Rev.D 95 (2017) no.3, 036022**]

Table: Contributions of $\Delta T = 0$ CP- violated couplings of meson and baryon interaction. All values have a factor $\bar{\theta}$.

Couplings	tree level	meson cloud	full
$g^{\rm CP}_{\pi NN}$	-0.02	-0.001	-0.021
$g^{\rm CP}_{\eta NN}$	-0.09	-0.003	-0.93
$g^{\rm CP}_{\eta' NN}$	-0.127	+0.002	-0.125

$$g^{\rm CP}_{\pi NN} = -\bar{\theta}\,\frac{m_d R}{F_\pi\,(1+R)}\,\langle N|\bar{q}\tau^3 q|N\rangle = -0.021\,\bar{\theta}\,, \tag{24}$$

$$g^{\rm CP}_{\eta NN} = -\frac{\bar{\theta}}{\sqrt{3}}\,\frac{m_d R}{F_\pi\,(1+R)}\,\langle N|\bar{q}q|N\rangle = -0.132\,\bar{\theta}\,, \tag{25}$$

$$g^{\rm CP}_{\eta' NN} = -\bar{\theta}\sqrt{\frac{2}{3}}\,\frac{m_d R}{F_\pi\,(1+R)}\,\langle N|\bar{q}q|N\rangle = -0.28\,\bar{\theta}\,, \tag{26}$$

Matrix elements $\langle N|\bar{q}\tau^3 q|N\rangle$ and $\langle N|\bar{q}q|N\rangle$ can be related to the nucleon axial charge g_A and pion-nucleon sigma-term $\sigma_{\pi N}$

$$\langle N|\bar{q}\tau^3 q|N\rangle = 1.022 \pm 0.080 \pm 0.060\,(\text{FLAG})\,, \tag{27}$$

$$\langle N|\bar{q}\tau^3 q|N\rangle = \frac{3}{5}\,g_A\,(\text{PCQM})\,, \tag{28}$$

$$\langle N|\bar{q}q|N\rangle = \frac{\sigma_{\pi N}}{\bar{m}} = 8.286\,, \tag{29}$$

where $\bar{m} = (m_u + m_d)/2 = 7$ MeV. For the $\sigma_{\pi N}$ we use the latest update 58 MeV.

Deuteron EDM // πNN coupling

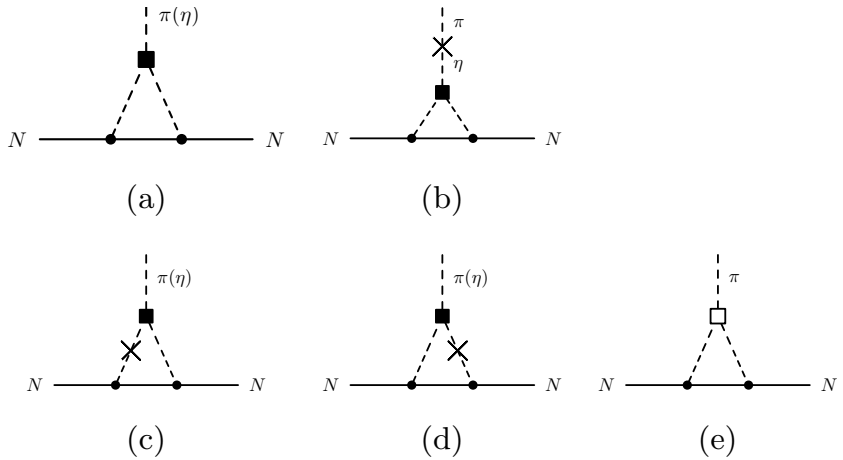


Figure: CP-violating πNN and ηNN couplings: (a) diagram induced by isospin-symmetric ($|\Delta T| = 0$) vertices; (b) and (c) diagrams induced by isospin-violating ($|\Delta T| = 1$) vertices induced by the *internal* $\pi^0 - \eta$ mixing; (d) diagram induced by isospin-violating ($|\Delta T| = 1$) pion-nucleon vertex and by the *external* $\pi^0 - \eta$ mixing. The cross symbol $\times$ denotes the $\pi^0 - \eta$ mixing; (e) diagram induced by CP-violating isospin-breaking coupling of three pseudoscalar mesons from Lagrangian (**??**). The black box symbol denotes the CP-violating isospin-symmetric P^3 vertex. The white box symbol denotes the CP-violating isospin-breaking P^3 vertex.

Finally, resulting contribution from one-meson exchange is:

$$|d_D^{\pi NN}| \quad = \quad 0.28 \cdot 10^{-18}\, \bar{\theta}\, \text{e cm}\,, \tag{30}$$

Our final prediction for the dEDM in terms of the $\bar{\theta}$ angle reads:

$$|d_D| = 0.482 \cdot 10^{-16}\, \bar{\theta}\, \text{e cm}\,. \tag{31}$$

Next using the upper limit for the $\bar{\theta}$ from data of neutron EDM we get

$$|d_D| < 2.2 \cdot 10^{-26}\, \text{e cm}\,. \tag{32}$$

Here we take into account that proton and neutron EDMs have different signs.

Conclusion

- Upper limits for rare decay widths of $\Gamma_{\eta\pi\pi}$ and $\Gamma_{\eta'\pi\pi}$ from EDM of neutron is much suppressed then we have from existed upper limits for these decay widths.

- Upper limit for the $\bar{\theta}$ parameter in the Peccei-Quinn mechanism:

$$|d_n| \simeq 0.67 \times 10^{-16}\ \bar{\theta}\mathrm{e}\cdot\mathrm{cm} \tag{33}$$

$\bar{\theta} < 4.4 \cdot 10^{-10}$ for PDG $|d_E^n| < 2.9 \times 10^{-26}\, e\cdot\mathrm{cm} R = 0.0.556$ (ChPT quark mass)

$\bar{\theta} < 2.6 \times 10^{-10}$ for current $|d_E^n| < 1.8 \times 10^{-26}\, e\cdot\mathrm{cm}$ and $R = 0.462$ (Lattice quark mass)

Same as for nEDM given by Crewther et al. (1979, 1980); and Pospelov and Ritz (1999) and Shindler et al. (2015) $d_n \simeq (10^{16}\mathrm{e}\cdot\mathrm{cm})\bar{\theta}$.

Conclusion

- A comparison between our theoretical prediction and sensitivity of future experimental measurements of the dEDM at the level of accuracy $\sim 10^{-29}$ from the EDM Collaboration gives more stringent limit on the CP-violating parameter $\bar{\theta}$:

$$|\bar{\theta}| < 2 \cdot 10^{-13} .$$

- We would like to stress that direct measurement of the decay rates of the CP-violation processes $\eta \to \pi\pi$ and $\eta' \to \pi\pi$ at level higher than limitations from data on EDMs could potentially signal about manifestation of New Physics.