CP-violation decays of η and η' mesons and EDM of neutron.

A.S. Zhevlakov (TSU, Russia)

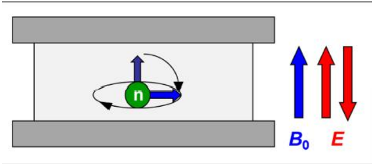
TSU

31 May 2018, Valday, Quarks-2018

Outline

- EDM of neutron, experimental limits
- CP- violation and axion
- CP-violated decay of η and η' mesons
- Estimation of EDM of neutron
- Our results

Determine Larmor precession frequency of Ultra Cold Neutron in E//B fields:



$$\left.\begin{aligned}\hbar\boldsymbol{\omega}_{\uparrow\uparrow} &= -2\mu_n B_0 - 2d_n E\\ \hbar\boldsymbol{\omega}_{\uparrow\downarrow} &= -2\mu_n B_0 + 2d_n E\end{aligned}\right\}$$

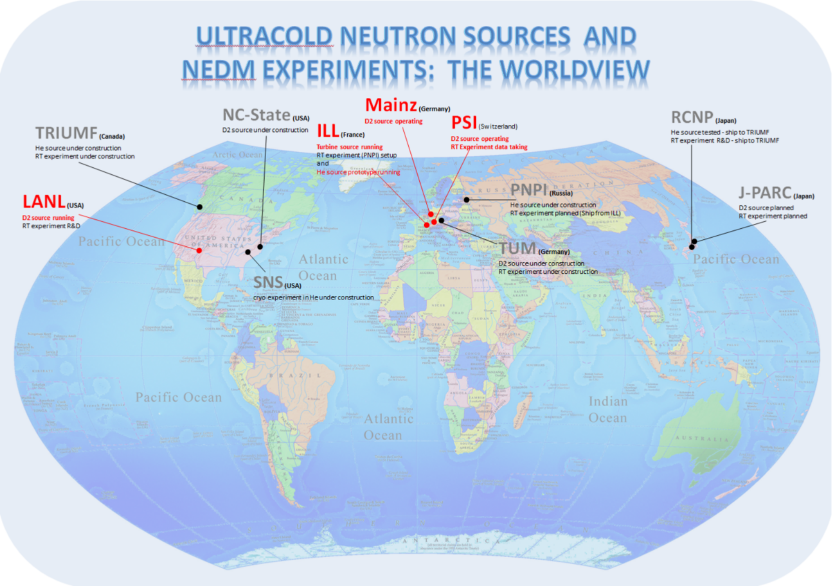
For $B_0 = const$ we have that

$$\hbar\Delta\omega = 2d_n E \tag{1}$$

This methods was proposed by N. Ramsey. It can help to separate oscillating fields.

Nobel prize 1989

Existed and future experiments



Existed and future experiments

Neutron EDM – Situation & Perspective

- **First Ramsey measurement**

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

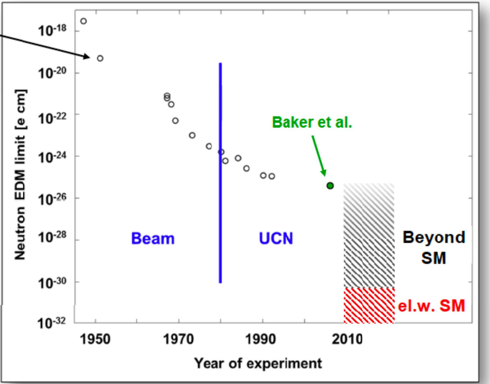
- **Current limit:**

$$\boxed{|d_n| < 2.9 \times 10^{-26}\ \text{e cm} \quad \text{(90\% CL)}}$$

Baker et al., PRL 97, 131801 (2006)

- **Sensitivity:**

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



13 Florian Piegsa – INT Workshop Seattle, WA – October 1st 2015

EDM Searches

System	Upper Limit [e cm]	Ref.	Comment
Neutron	3.0×10^{-26} (90%CL)	[1]	direct limit
Muon	1.9×10^{-19} (95% CL)	[2]	direct limit
^{199}Hg	3.1×10^{-29} (95% CL)	[3]	best dir. limit of any EDM & indir. limit for proton: $d_p < 7.9 \times 10^{-25}$ e cm (also provides indir. limits for n & e)
^{205}Tl	9×10^{-25} (90% CL)	[4]	used to set a limit for the electron: $d_e < 1.6 \times 10^{-27}$ ecm
YbF	1.1×10^{-22} (90% CL)	[5]	$d_e < 1.05 \times 10^{-27}$ ecm
ThO		[6]	$d_e < 8.7 \times 10^{-29}$ ecm
Xe, Ra, Rn, … p, d, … Molecules, …			

[1] Baker et al., PRL 97, 131801 (2006), Pendlebury et al., arXiv:1509.04411
[2] Bennett et al., PRD 80, 052008 (2009)
[3] Griffith et al., PRL 102, 101601 (2009)
[4] Regan et al., PRL 88, 071805 (2002)
[5] Hudson et al., Nature 473, 493 (2011)
[6] ACME Collaboration, Science 343, 269 (2014)

Diamagnetic atom
Paramagnetic atom
Paramagnetic/Polar molecule

12 Florian Piegsa – INT Workshop Seattle, WA – October 1st 2015

CP-violation in Strong Interaction Sector

Quantum Chromodynamics (QCD) describes the strong interactions of hadrons in terms of the interactions of their quark and gluon constituents. The QCD Lagrangian

$$\mathcal{L}_{\mathrm{QCD}} = -\sum_f \bar{q}_f \left(\gamma^\mu \frac{1}{i} D_\mu + m_f \right) q_f - \frac{1}{4} G_a^{\mu\nu} G_{a\mu\nu} \tag{2}$$

for f flavors of quarks has a large global symmetry in the limit when $m_f \to 0:\ G = U(f)_{\mathrm{R}} \times U(f)_{\mathrm{L}}$. This symmetry corresponds to the freedom of arbitrary chiral rotations of the f flavor of quarks into each other. Because $m_u, m_d \ll \Lambda_{\mathrm{QCD}}$—with Λ_{QCD} being the dynamical scale of the theory—in practice only a chiral $U(2)_{\mathrm{R}} \times U(2)_{\mathrm{L}}$ symmetry is actually a very good approximate global symmetry of the strong interactions.

The richer vacuum of QCD, combined with the violation of CP in the weak interactions, allows for the presence of an effective interaction

$$\mathcal{L}_{\mathrm{strong\ CP}} = \bar{\theta} \frac{\alpha_s}{8\pi} G_{a\mu\nu} \tilde{G}_a^{\mu\nu} \tag{3}$$

which leads to an enormous neutron electric dipole moment $\left[d_n \sim e\bar{\theta}(m_q/M_N^2) \right]$, unless the parameter $\bar{\theta}$ is tiny ($\bar{\theta} \leq 10^{-9}$).

The effective action which included a θ -term

$$S_{\text{eff}} = S[A] + \theta \frac{\alpha_s}{8\pi} \int d^4x G_a^{\mu\nu} \tilde{G}_{a\mu\nu} \ . \tag{4}$$

This additional term violates P and CP, since it corresponds to an $\vec{E}_a \cdot \vec{B}_a$ interaction of the color fields.
Perturbation theory is connected to the $\nu = 0$ sectors where the $G\tilde{G}$ term vanishes. The effects of the $\nu \neq 0$ sectors thus necessarily are nonperturbative. These contributions are naturally selected by the connection of $G\tilde{G}$ to the chiral anomaly. For n_f flavors, the axial current J_5^μ has an anomaly

$$\partial_\mu J_5^\mu = n_f \frac{\alpha_s}{8\pi} G_{a\mu\nu} \tilde{G}_a^{\mu\nu}. \tag{5}$$

The solution to the $U(1)_{\mathrm{A}}$ problem is connected to the chirality breakdown in QCD in the $\nu \neq 0$ sectors. Where

$$\nu = \frac{\alpha_s}{8\pi} \int d^4x G_{a\mu\nu} \tilde{G}_a^{\mu\nu} \ . \tag{6}$$

To restore of CP symmetry, Peccei and Quinn suggested change θ to $\theta(x)$, and decomposed it into an axial field $a(x)$ (axion) that preserves CP conservation, and a small constant $\bar{\theta}$ that encodes the CP-violating effect.

Figure: The $\eta(\eta') \to \pi\pi$ decay process. The solid square represents the CP-violating vertex.

In framework of QCD rules was founded transition amplitude for decay η or η' mesons into pion pair [Shifman, Vainshtein, Zaharov NPB166(1980)]

$$A(\eta \to \pi^+\pi^-) \simeq \theta \frac{m_\pi^2}{\sqrt{6} f_\pi} \frac{4 m_u m_d}{(m_u + m_d)^2} \tag{7}$$

where was showed a connection CP-violation decay with theta term of QCD lagrangian.

Figure: The $\eta(\eta') \to \pi\pi$ decay process. The solid square represents the CP-violating vertex.

The current direct experimental 90% C.L. upper limits for CP-violated decays of η and η' mesons

$$\frac{\Gamma(\eta \to \pi\pi)}{\Gamma_{\eta}^{\text{tot}}} < \begin{cases} 1.3 \times 10^{-5} \text{ for } \pi^+\pi^- \\ 3.5 \times 10^{-4} \text{ for } \pi^0\pi^0 \end{cases} ,$$

$$\frac{\Gamma(\eta' \to \pi\pi)}{\Gamma_{\eta'}^{\text{tot}}} < \begin{cases} 1.8 \times 10^{-5} \text{ for } \pi^+\pi^- \\ 4.0 \times 10^{-4} \text{ for } \pi^0\pi^0 \end{cases}$$

Data of the LHCb Collaboration Phys.Lett.B764 (2017) and PDG data

Phenomenology Lagrangian which described decay $H = \eta(\eta')$ into two pions have a form

$$\mathcal{L}^{\mathsf{CP}}_{H\pi\pi} = f_{H\pi\pi}\, M_H\, H\, \vec{\pi}^{\,2} \tag{8}$$

The decay width is given by

$$\Gamma = \frac{|\vec{p}_\pi|}{16\pi\, m_H^2}\, |\mathcal{M}_{H\pi^0\pi^0}|^2 = \frac{1}{2}\frac{\sqrt{M_H^2 - 4M_\pi^2}}{4\pi}\, |f_{H\pi^0\pi^0}|^2\,, \tag{9}$$

$$\Gamma = \frac{|\vec{p}_\pi|}{8\pi\, m_H^2}\, |\mathcal{M}_{H\pi^+\pi^-}|^2 = \frac{\sqrt{M_H^2 - 4M_\pi^2}}{4\pi}\, |f_{H\pi^+\pi^-}|^2\,, \tag{10}$$

the lower result as the global upper limit:

$$\begin{aligned} |f_{\eta\pi\pi}| &< 2.1 \times 10^{-5}, \\ |f_{\eta'\pi\pi}| &< 2.2 \times 10^{-4}\,. \end{aligned} \tag{11}$$

For the leading non-vanishing order EDM calculation on account of CP-violated η and η' mesons into two pions, the values of $f_{\eta\pi\pi}$ and $f_{\eta'\pi\pi}$ at $s=0$ are needed. The solution for partial wave amplitudes with isospin I and total spin J is known in the form of the Omnes-Muskhilishvili (OM) function obtained from the experimentally known phase in each partial wave,

$$\Omega_{IJ}(s) = exp\left[\frac{s}{\pi}\int_{4m_\pi^2}^{\infty}\frac{ds'\delta_{IJ}(s')}{s'(s'-s-i\epsilon)}\right] \tag{12}$$

with δ_{IJ} the respective phase shift. In our particular case, there is only the s-wave $I=J=0$. We use the fit to $\pi\pi$ scattering data by Pelaez and Yndurain who provided an analytical form for $\delta_{00}(s)$ in the region $4m_\pi^2 \leq s \leq 1.42^2$ GeV^2. The effect of the rescattering is then reassumed as

$$f_{\eta\pi\pi}(s) = f_{\eta\pi\pi}(0)\Omega(s). \tag{13}$$

Evaluating the OM function at the $\eta(\eta')$ meson mass, we obtain

$$|f_{\eta\pi\pi}(m_\eta^2)| = 1.81|f_{\eta\pi\pi}(0)|, \tag{14}$$
$$|f_{\eta'\pi\pi}(m_{\eta'}^2)| = 4.46|f_{\eta'\pi\pi}(0)|. \tag{15}$$

This procedure allows one to account for a CPV $\eta-\sigma$ and $\eta'-f_0(980)$ mixing.
The experimental limits can finally be translated into bounds on the coupling constants,

$$\begin{aligned} |f_{\eta\pi\pi}(0)| &\lesssim 1.2\times 10^{-5} \\ |f_{\eta'\pi\pi}(0)| &\lesssim 4.9\times 10^{-5}. \end{aligned} \tag{16}$$

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

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

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 $d_n^E = -F_D(0)/(2m_N)$.

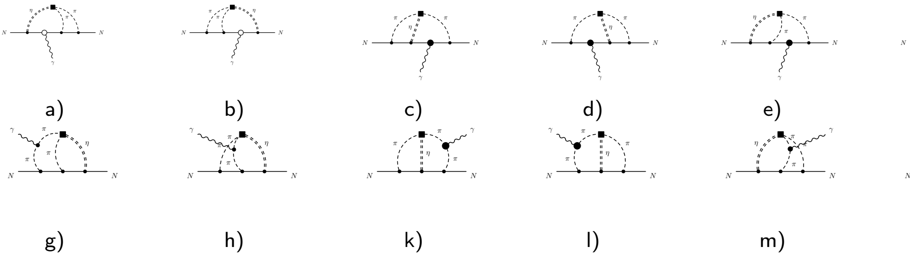
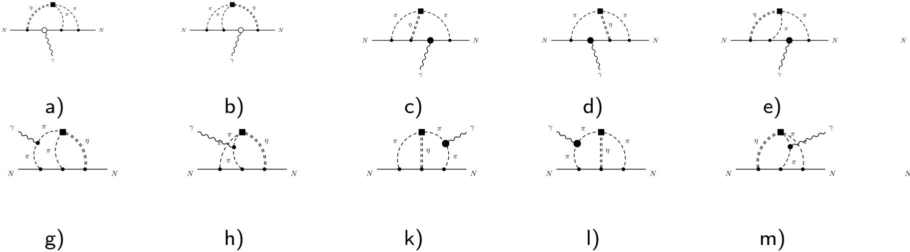


Figure: Diagrams describing the nEDM in the framework of PS interactions between mesons and baryons. The interaction with the external electromagnetic field occurs through the minimal electric coupling to charged baryon or meson fields. The solid square denotes the CP-violating $\eta\,\pi^+\pi^-$ vertex.

EDM of neutron



We will use simple pseudoscalar approach of baryon and pseudoscalar fields interaction for EDMn calculation [Weinberg book]. Vertex of interaction between baryon and pseudoscalar fields has a form

$$-2iM_N \frac{g_A}{F_\pi} \pi^a \bar{N} \gamma_5 \tau^a N, \tag{17}$$

EDM of neutron

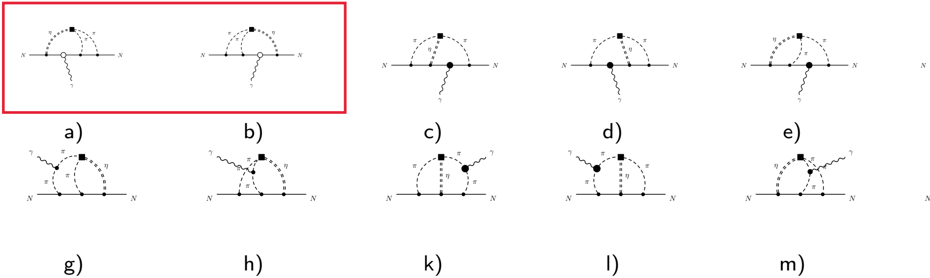


Figure: Diagrams describing the nEDM in the framework of PS interactions between mesons and baryons. The interaction with the external electromagnetic field occurs through the minimal electric coupling to charged baryon or meson fields. The solid square denotes the CP-violating $\eta\,\pi^+\pi^-$ vertex.

First to diagrams was also calculated into account intermediate baryon states Δ [Phys. Rev. D91, 085017 (2015)]

Estimated value of EDM of neutron

$$d_n^E \simeq (8.8 f_{\eta\pi\pi}(m_\eta^2) + 9.8 f_{\eta'\pi\pi}(m_\eta^2)) \times 10^{-14} \text{e} \cdot \text{cm}. \quad (18)$$

By using the current experimental constraint $|d_E^n| < 2.9 \times 10^{-26}\, e \cdot \mathrm{cm}$, we compute the upper limits to the rare decay constants from the theory side. When assuming no correlation between the coupling constants, they read:

$$|f_{\eta\pi\pi}(0)| < 0.33 \times 10^{-12}, \quad (19)$$

$$|f_{\eta'\pi\pi}(0)| < 0.29 \times 10^{-12}\,. \quad (20)$$

Thus, the boundary values for the rare decay widths $\Gamma_{\eta\pi\pi}$ and $\Gamma_{\eta'\pi\pi}$ are strongly suppressed when compared to the existing data [LHCb]

$$\Gamma(\eta \to \pi\pi) < 0.47 \times 10^{-20}\, \text{keV}, \quad (21)$$

$$\Gamma(\eta' \to \pi\pi) < 0.39 \times 10^{-20}\, \text{keV}. \quad (22)$$

Summary

- 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:

$$\bar{\theta} < 0.6 \cdot 10^{-11}\,.$$

- Question about other mechanism which can play a role in rare decau of $\eta \to 2\pi$ is opened.

Thank you for attention!

Work of studying EDM of neutron was made in collaboration with: Valery E. Lyubovitskij, Astrid N. Hiller Blin, Thomas Gutsche, Mikhail Gorchtein, S. Kovalenko, S. Kuleshov, M. J. Vicente Vacas.

This work has been done in framework of TSU Competitiveness Enhancement Programme 2013-2020.