EDM bounds on Light Scalar Particles

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Introduction

Long-standing motivations for believe in existence of $(pseudo-)scalar\ bosons$ extending the SM particle spectrum – *"New macroscopic forces?" - J.E. Moody* $\&$ *F. Wilczek*

Small value for *neutron electric dipole moment (EDM)* lead to introduction of $axions$ to resolve *strong* CP *problem*

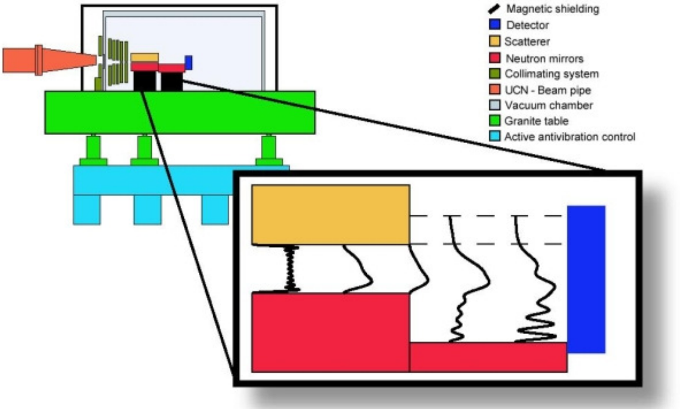
Comparison of experimental bounds on $new\ hypothetical\ scalars$ by high-precision "fifth-force" experiments vs EDMs

Introduction

- Experiments
  1. *"Fifth-Force" Experiments*
  2. *EDM*
- "Fifth-Force" & EDM bounds
  1. *Axions*
  2. *Scalars w/o PQS*
- Conclusion
- Outlook

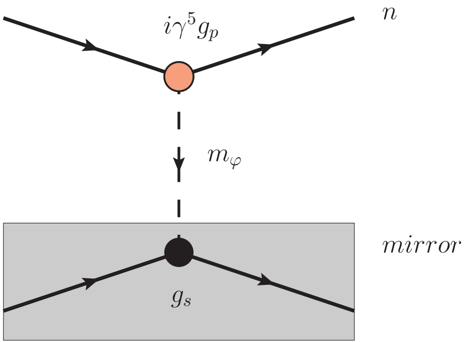
1. "Fifth-Force" Experiments

Host of different "fifth-force" experiments
(e.g. *nQ-bouncer, NMR frequency shift, . . .*)



"n count rate (z)" $\Longrightarrow$ $|\psi(z)|^2$

1. "Fifth-Force" Experiments: nQ-bouncer



$$\delta V(r) = g_s g_p \frac{\vec{\sigma}_n \cdot \vec{e}_r}{8\pi m_n} \left(\frac{m_\varphi}{r} + \frac{1}{r^2} \right) e^{-m_\varphi r} \quad \Longrightarrow \quad \delta\psi(z;\sigma_n)$$

from the *3 possible exchanges* $g_s g_s$, $g_s g_p$ and $g_p g_p$
only $g_s g_p$ violates P and T (and hence CP if CPT holds)

1. "Fifth-Force" Experiments: nQ-bouncer

(Pseudo-)scalar Vertices

$$\mathcal{L} = g_s \, \varphi \, \bar{\psi}\psi$$

$$\mathcal{L} = g_p \, \varphi \, \bar{\psi} \, i\gamma^5 \psi$$

Amplitude

$$\mathcal{M} = -g_s g_p \, \bar{u}_m(k')u_m(k) \, \frac{1}{q^2 - m_\varphi^2} \, \bar{u}_n(p') \, i\gamma^5 u_n(p)$$

$$n.r. \to -g_s g_p \, 2m_n \, \frac{1}{\vec{q}^{\,2} + m_\varphi^2} \, i \, \vec{\sigma}_n \cdot \vec{q}$$

Fourier Transformation gives Potential

$$V(r) = g_s g_p \, \frac{\vec{\sigma}_n \cdot \vec{e}_r}{8\pi m_n} \left(\frac{m_\varphi}{r} + \frac{1}{r^2} \right) e^{-m_\varphi r}$$

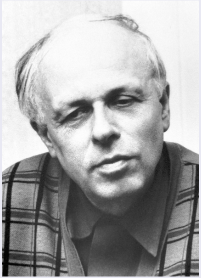
2. Electric Dipole Moments

EDM signals P & T violation (& if CPT holds)
CP violation

"Sakharov" conditions (1967)

for observed anti-/matter asymmetry in universe

1. Baryon number violation
2. C & CP violation
3. Interactions out of thermal equilibrium



SM - CP violation **"too small"** for observed asymmetry

2. Electric Dipole Moments

REVIEW OF PARTICLE ELECTRIC DIPOLE MOMENTS

J. Mike Pendlebury
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Abstract

The connection between permanent electric dipole moments of particles and CP violation is discussed and the current state of comparison between experimental results and theoretical predictions for electric dipole moments is reviewed. The most recent experiments are summarised and comments are made on the potential for future progress.

"n-EDM has killed more theories than any other single experiment"

2. Electric Dipole Moments

"Energy Scale Map" of CPV

BSM CPV *(SUSY, GUTs, extra Dim. . .)*

$\Updownarrow$

EW Scale Operators $\mathcal{L}_{\text{eff}} = \sum \frac{C}{\Lambda^2_{BSM}} \mathcal{O}$

$\Updownarrow$

Had Scale Operators $\mathcal{L}_{\text{eff}} = \sum \frac{C \langle H^0 \rangle}{\Lambda^2_{BSM}} \mathcal{O}'$

$\Updownarrow$

QCD Matrix Elements $d_n, \bar{g}_{\pi NN}, \ldots$

$\Updownarrow$

Experiment

2. Electric Dipole Moments

EDM

$$H = -\vec{d} \cdot \vec{E} = -d \, \frac{\vec{S}}{S} \cdot \vec{E}$$

EDM relativistic spin-1/2 particle

$$\mathcal{L} = -i \, \frac{d}{2} \, \bar{\psi} \sigma^{\mu\nu} \gamma^5 \psi \, F_{\mu\nu}$$

Experimental bounds at 90 % C.L.

$$|d_n| < 2.9 \times 10^{-13} \, \mathrm{e\,fm}$$

$$|d_e| < 10.5 \times 10^{-15} \, \mathrm{e\,fm}$$

$$|d_{Hg}| < 2.6 \times 10^{-16} \, \mathrm{e\,fm}$$

Part A: Axions

QCD θ-term

QCD θ-term

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

Only CP violating *dimension 4 operator* (SM)

$CP(\vec{E}_G \cdot \vec{B}_G) = -\vec{E}_G \cdot \vec{B}_G$

No suppression by heavy scale $\Lambda \Longrightarrow$

Large *neutron EDM* (*strong CP problem*)

Total derivative term ($\Longrightarrow$ no Feynman diagrams)

QCD θ-term

Generating Functional

$$Z[J] = \int \mathcal{D}\psi \mathcal{D}\bar{\psi} \, e^{i \int d^4x \, \theta \, \frac{g_s^2}{32\pi^2} \, \tilde{G}^a_{\mu\nu} G^{a\mu\nu}} \ldots$$

Physics **must be invariant** under transformation of *dummy integration variable* ψ, $\bar{\psi}$

$$\psi \to e^{-i\alpha\gamma^5} \psi$$
$$\bar{\psi} \to \bar{\psi} \, e^{-i\alpha\gamma^5}$$

Transformation of Path Integral Measure & QCD θ-term

$$\mathcal{D}\psi \mathcal{D}\bar{\psi} \to \mathcal{D}\psi \mathcal{D}\bar{\psi} \, e^{i \int d^4x \, \frac{g_s^2 \alpha}{16\pi^2} \, \tilde{G}^a_{\mu\nu} G^{a\mu\nu}}$$
$$\theta \to \theta + 2\alpha$$

QCD θ-term

$U(1)_A$ Transformation of Lagrangian ($N_f = 1$)

$$\mathcal{L} = \theta \frac{g_s^2}{32\pi^2} \tilde{G}^a_{\mu\nu} G^{a\mu\nu} + \bar{\psi} i \not{D} \psi - m \bar{\psi}\psi$$

$$\downarrow \quad U(1)_A$$

$$\mathcal{L} = \bar{\psi} i \not{D} \psi - m \cos\theta\, \bar{\psi}\psi + m \sin\theta\, \bar{\psi}\, i\gamma^5 \psi$$

$$\downarrow \quad \mathcal{O}(\theta)$$

$$\mathcal{L} = \bar{\psi} i \not{D} \psi - m \bar{\psi}\psi + m\, \theta\, \bar{\psi}\, i\gamma^5 \psi$$

Physical Consequences

- For *vanishing quark mass* θ-term can be rotated away and becomes *unphysical*
- **Physical (invariant)** quantity $\bar{\theta} = \theta + \arg\det m$
- *Strong CP problem*: Why is $\bar{\theta}$ so small?

Axions

Consider adding to the SM a *complex scalar field* Φ and *massless quark* ψ with *Yukawa coupling* y

Lagrangian

$$\mathcal{L}_{PQ} = \partial_\mu \Phi^\dagger \partial^\mu \Phi + \mu^2 \Phi^\dagger \Phi - \lambda \left(\Phi^\dagger \Phi\right)^2 + \bar{\psi} i \not{D} \psi + y\, \Phi\, \bar{\psi}_R \psi_L + h.c.$$

Peccei-Quinn Symmetry

$\mathcal{L}_{SM} + \mathcal{L}_{PQ}$ *invariant* under *global chiral* $U(1)_{PQ}$ *transformation*

$$\psi \to e^{-i\alpha\gamma^5} \psi, \quad \bar{\psi} \to \bar{\psi}\, e^{-i\alpha\gamma^5}, \quad \Phi \to e^{-2i\alpha}\, \Phi$$

Spontaneous breaking of $U(1)_{PQ}$ leads to *massless pseudo-scalar goldstone boson* – the axion $\mathrm{a}(x)$

$$\Phi(x) = \frac{f_a + \rho(x)}{\sqrt{2}}\, e^{i\mathrm{a}(x)/f_a}$$

Axions

Peccei-Quinn Symmetry

$$\bar{\theta} \to \bar{\theta} + 2\alpha \quad \& \quad \frac{\mathrm{a}(x)}{f_a} \to \frac{\mathrm{a}(x)}{f_a} - 2\alpha$$

Hence the **physical (invariant)** quantity becomes

$$\bar{\theta} + \frac{\mathrm{a}(x)}{f_a}$$

Kinetic Term

$$\partial_\mu \Phi^\dagger \partial^\mu \Phi = \frac{1}{2}\,\partial_\mu \mathrm{a} \partial^\mu \mathrm{a} + \dots$$

The "Total θ"

$$\underbrace{\overbrace{\theta + \arg\det m}^{\bar{\theta}} + \frac{\langle \mathrm{a} \rangle}{f_a}}_{\bar{\theta}_{ind}} + \frac{a(x)}{f_a} \qquad \textit{with} \qquad \mathrm{a}(x) = \langle \mathrm{a} \rangle + a(x)$$

Axions

$U(1)_A$ Transformation of SM Lagrangian ($N_f = 1$)

$$\mathcal{L} = \left(\bar{\theta}_{ind} + \frac{a(x)}{f_a}\right) \frac{g_s^2}{32\pi^2} \tilde{G}^a_{\mu\nu} G^{a\mu\nu} + \bar{\psi} i \not{D} \psi - m \bar{\psi}\psi$$

$$\downarrow \quad U(1)_A$$

$$\mathcal{L} = \bar{\psi} i \not{D} \psi - m \cos\left(\bar{\theta}_{ind} + \frac{a(x)}{f_a}\right) \bar{\psi}\psi + m \sin\left(\bar{\theta}_{ind} + \frac{a(x)}{f_a}\right) \bar{\psi}\, i\gamma^5 \psi$$

$$\downarrow$$

$$\mathcal{L} = \bar{\psi} i \not{D} \psi - m \bar{\psi}\psi + \frac{m\,\bar{\theta}_{ind}^2}{2} \bar{\psi}\psi + \frac{m}{2f_a^2} a^2 \bar{\psi}\psi + m\,\bar{\theta}_{ind}\, \bar{\psi}\, i\gamma^5 \psi$$

$$+ \underbrace{\frac{m\,\bar{\theta}_{ind}}{f_a}}_{g_s^q} a\bar{\psi}\psi + \underbrace{\frac{m}{f_a}}_{g_p^q} a\bar{\psi}\, i\gamma^5 \psi + \dots$$

Axions

$$\mathcal{L} = \frac{1}{2}\,\partial_\mu a \partial^\mu a + \frac{m}{2f_a^2}\langle\bar{\psi}\psi\rangle\, a^2$$

Due to **non-perturbative QCD** the *axion* is a *pseudo-Goldstone boson*

Axion solves the *strong CP problem* since

$$V = -\frac{m}{2}\langle\bar{\psi}\psi\rangle\left(\bar{\theta} + \frac{\langle a\rangle}{f_a}\right)^2$$

– **dynamical relaxation**

Axions

Experimental constraints by *(in)direct searches*: $f_a \gtrsim 10^9$ GeV

Cosmological constraints: $f_a \lesssim 10^{12}$ GeV

QCD effects may induce **linear term** in *axion potential* in the presence of other **CP odd operators** at *low scales*

$$V = \alpha \left(\bar{\theta} + \frac{\langle a \rangle}{f_a} \right) - \frac{m}{2} \langle \bar{\psi} \psi \rangle \left(\bar{\theta} + \frac{\langle a \rangle}{f_a} \right)^2$$

The *minimum* of this *axion potential* is the *induced theta term*

$$\bar{\theta}_{ind} = \left(\bar{\theta} + \frac{\langle a \rangle}{f_a} \right)_{min}$$

The *induced theta term* is **NOT** in conflict with *neutron EDM*

Axions

Leading source of EDM

$$\mathcal{L} = m\,\bar{\theta}_{ind}\,\bar{\psi}\,i\gamma^5\psi$$

Induces *CP violating propagator correction*

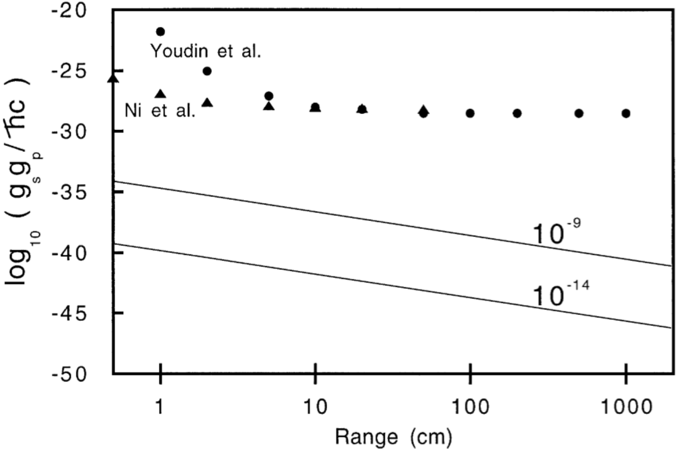
$$\frac{i}{\not{k} - m} \to \frac{i}{\not{k} - m} + \frac{im}{k^2 + m^2}\,\bar{\theta}_{ind}\,i\gamma^5$$

Sub-leading source of EDM by "one axion-exchange"

$$g_s^q = \frac{m\,\bar{\theta}_{ind}}{f_a} \qquad \& \qquad g_p^q = \frac{m}{f_a}$$

induces *axion mediated "fifth-force"*

This implies that *EDM measurements* put bounds on $\bar{\theta}_{ind}$ and thus on g_s^q



$$g_s^q g_p^q = \frac{m^2\,\bar{\theta}_{ind}}{f_a^2} \propto \frac{\bar{\theta}_{ind}}{\lambda^2}$$

Part B: Scalar w/o PQ Symmetry

Scalar w/o PQ Symmetry

General Scalar

NOT related to a *PQ symmetry* $\Longrightarrow$
couplings g_s, g_p and mass m are *a priori* **free parameters**

NO relation to QCD θ-term

EDM is induced by exchange of one scalar with coupling g_s and g_p – *CPV interaction*

In following analysis we assume the *scalar* to couple to *quarks (hadrons)*

Coupling to *lepton* and *photons* is neglected ($\sim$ *axion*)

Schiff Moment

EDMs are obtained by applying **external (anti-)parallel $\vec{E}_{ext}$ and $\vec{B}_{ext}$ fields** and measuring the *Larmor precession frequency shift*

Schiff Theorem

Assumptions:

- *Neutral atom*
- *Point-like constituents*
- *Non-relativistic*

Classical picture: Each *constituent of a neutral atom* must not be accelerated by an *external electric field* $\vec{E}_{ext}$. Hence, the *constituents* must rearrange in such a way, that the *induced electric field* $\vec{E}_{int}$ screens the external field at the locations $\vec{r}_i$ of each *constituent*, i.e. $\vec{E}_{int}(\vec{r}_i) = -\vec{E}_{ext}$.

Schiff Moment

Due to the **vanishing effective electric field**, an EDM of a constituent cannot lead to a *Larmor precession frequency shift* $\Longrightarrow$ EDM *unobservable*

Schiff theorem holds **quantum-mechanically**

Violations:

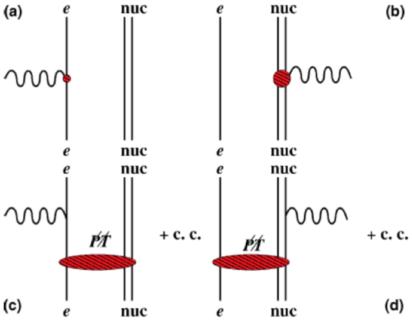
- *Non-pointlike constituents*
- *Relativistic corrections*
- *CPV interactions between constituents can evade Schiff screening*

Fundamental quantity is **Schiff moment**

$$\vec{S} \sim \int d^3x\, x^2\, \vec{x}\, \rho(\vec{x})^{CPV}$$

^{199}Hg – Electric Dipole Moment

Atomic–EDM Contributions

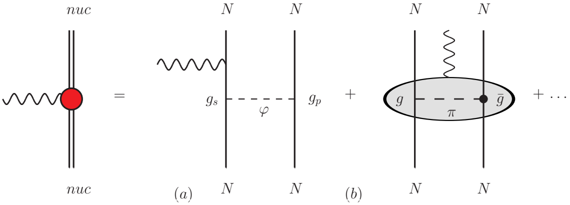


Scalar coupling to *quarks* (and hence π, N) but **NOT** to *electrons* and *photons*

$\Longrightarrow$ **non-vanishing contribution** only from (b)

^{199}Hg – Electric Dipole Moment

Nucleus–EDM Contributions



(a) *leading contribution*

direct scalar exchange – **NO** nuclear calculation available

(b) *sub-leading contribution*

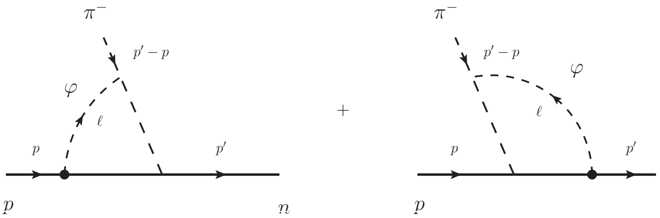
CPV π – exchange

"loop-suppressed" ($\sim$ 2 orders of magnitude)

– nuclear calculation available

$CPV\ \bar{N}N\pi$ – Vertex

Two contributions to a *$CPV\ \bar{N}N\pi$ – vertex* are *leading* and *not suppressed*



Scalar coupling g_s^π at π, *pseudo – scalar* coupling g_p at N
Diagrams evaluated with *Heavy Baryon χPT*

Heavy Baryon χPT

Heavy Baryon χPT

Velocity dependent field decomposition of the *nucleon $SU(2)$ isospinor*

$$L_v(x) = e^{imv\cdot x} P_v^+ \Psi(x)$$
$$H_v(x) = e^{imv\cdot x} P_v^- \Psi(x)$$

$$P_v^\pm = \frac{1 \pm \not{v}}{2} \quad , \quad v^2 = 1$$

Inverse field decomposition

$$\Psi(x) = e^{-imv\cdot x}\left(L_v(x) + H_v(x)\right)$$

Integrating out heavy fields $H_v(x)$ in the *generating functional path integral* yields *$HB\chi PT$* **propagators** and **vertices**

$CPV\ \bar{N}N\pi$ – Vertex

Propagator & Spin operator

$$G_{HB}(k) \simeq \frac{iP_v^+}{v\cdot k + i\varepsilon} \quad , \quad G_0(k) = \frac{i}{k^2 - m^2 + i\varepsilon}$$

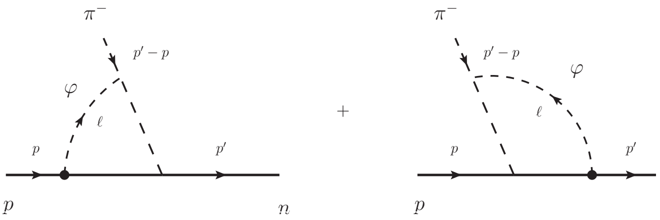
$$S_\mu = \frac{i}{2}\gamma^5\sigma_{\mu\nu}v^\nu$$

Lagrangians of the *vertices*

χPT	$HB\chi PT$
$\mathcal{L}_{\pi\bar{N}N} = \frac{g_A}{f_\pi}\,\partial_\mu\pi^a\,\bar{N}\,\frac{\sigma^a}{2}\gamma^\mu\gamma^5 N$	$\sim \frac{2g_A}{f_\pi}\,\partial_\mu\pi^a\,\bar{N}_v\,\frac{\sigma^a}{2}S^\mu N_v$
$\mathcal{L}_{\varphi\pi\pi} = g_s^\pi\,\varphi\,\pi^a\pi^a$	$\sim g_s^\pi\,\varphi\,\pi^a\pi^a$
$\mathcal{L}_{\varphi\bar{N}N} = g_p\,\varphi\,\bar{N}\,i\gamma^5 N$	$\sim -\frac{g_p}{m_N}\,\bar{N}_v\,(S^\mu\partial_\mu\varphi)\,N_v$

$CPV\ \bar{N}N\pi$ – Vertex

Calculation of the loop in the limit $q^2 \to 0$



Effective Lagrangian for $CPV\ \bar{N}N\pi$ – vertex

$$\mathcal{L}^{CPV}_{\pi\bar{N}N} = \frac{1}{16\pi}\frac{m_\pi^2 + m_\pi m_\varphi + m_\varphi^2}{m_\pi + m_\varphi}\frac{g_s^\pi g_p g_A}{m_N f_\pi}\,\pi^a \bar{N}\,\sigma^a N$$

$$\simeq \frac{g_s^\pi g_p}{16\pi}\frac{m_\pi g_A}{m_N f_\pi}\,\pi^a \bar{N}\,\sigma^a N \quad \text{for} \quad m_\varphi \ll m_\pi$$

$CPV\ \bar{N}N\pi$ – Vertex

$$\mathcal{L}^{CPV}_{\pi\bar{N}N} \simeq \frac{g_s^{\pi}\, g_p}{16\pi}\, \frac{m_\pi g_A}{m_N f_\pi}\, \pi^a \bar{N}\, \sigma^a N$$

Leading non-derivative CP violating $\pi\bar{N}N$ vertex

$$\mathcal{L} = \bar{g}^{(0)}_{\pi NN}\, \pi^a \bar{N}\, \sigma^a N + \bar{g}^{(1)}_{\pi NN}\, \pi^0 \bar{N} N + \bar{g}^{(2)}_{\pi NN}\left(\pi^a \bar{N}\, \sigma^a N - 3\, \pi^0 \bar{N}\, \sigma^3 N\right)$$

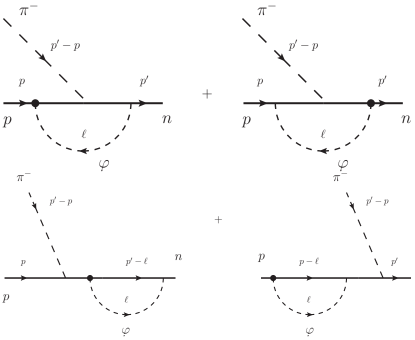
$$\bar{g}^{(0)}_{\pi NN} \simeq \frac{g_s^{\pi}\, g_p}{16\pi}\, \frac{m_\pi g_A}{m_N f_\pi}$$

$$\bar{g}^{(1)}_{\pi NN} = 0$$

$$\bar{g}^{(2)}_{\pi NN} = 0$$

$CPV\ \bar{N}N\pi$ – Vertex

More contributions/diagrams to a *$CPV\ \bar{N}N\pi$ – vertex*



Depicted above are some *sub-leading* contributions **suppressed** due to $1/m_N$

Form Factors

For **comparison** with "fifth-force" experiments – $g_s^\pi(g_s)$

Scalar – pion coupling

$$\mathcal{L}_{\varphi\pi\pi} = g_s^\pi\,\varphi\,\pi^a\pi^a$$

Scalar – quark coupling

$$\mathcal{L}_{\varphi\bar{q}q} = g_s^q\,\varphi\sum_{u,d,s}\bar{q}q$$

Scalar – nucleon coupling

$$\mathcal{L}_{\varphi\bar{N}N} = g_s\,\varphi\,\bar{N}N$$

Form Factors

Scalar – nucleon coupling

$$\frac{g_s^\pi}{g_s} = \frac{\langle \pi | \bar{u}u + \bar{d}d | \pi \rangle}{\langle N | \bar{u}u + \bar{d}d | N \rangle}$$

J. R. Ellis, J. S. Lee and A. Pilaftsis, JHEP **0810** (2008) 049

$$\langle N | \bar{u}u + \bar{d}d | N \rangle = \frac{90\,\mathrm{MeV}}{m_u + m_d}$$

Neglecting isospin breaking

$$\langle \pi | \bar{u}u + \bar{d}d | \pi \rangle = \frac{m_\pi^2}{m_u + m_d}$$

Final Result

$$\frac{g_s^\pi}{g_s} = \frac{m_\pi^2}{90\,\mathrm{MeV}} = 218\,\mathrm{MeV}$$

Nuclear calculation [a] (πNN coupling $g = 13.5$)

[a] J. H. de Jesus, J. Engel, Phys. Rev. C 72, 045503 (2005)

$$S(^{199}Hg) = g\left(0.01\,\bar{g}^{(0)}_{\pi NN} + 0.07\,\bar{g}^{(1)}_{\pi NN} + 0.02\,\bar{g}^{(2)}_{\pi NN}\right)\mathrm{e\,fm}^3$$

^{199}Hg–EDM in terms of **Schiff moment**

$$d(^{199}Hg) = -2.8\times 10^{-4}\,\frac{S(^{199}Hg)}{\mathrm{fm}^2}$$

Experimental Bound on ^{199}Hg–EDM (95 % C.L.) is [a]

[a] W. C. Griffith, *et al.*, PRL 102, 101601 (2009)

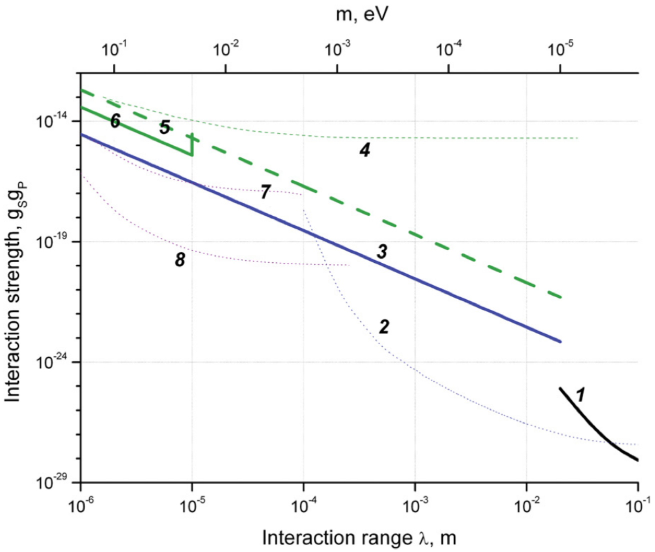
$$|d(^{199}Hg)| < 3.1\times 10^{-16}\,\mathrm{e\,fm}$$

Final result for $m_\varphi \ll m_\pi$

$$|g_s g_p| < 1\times 10^{-9}$$

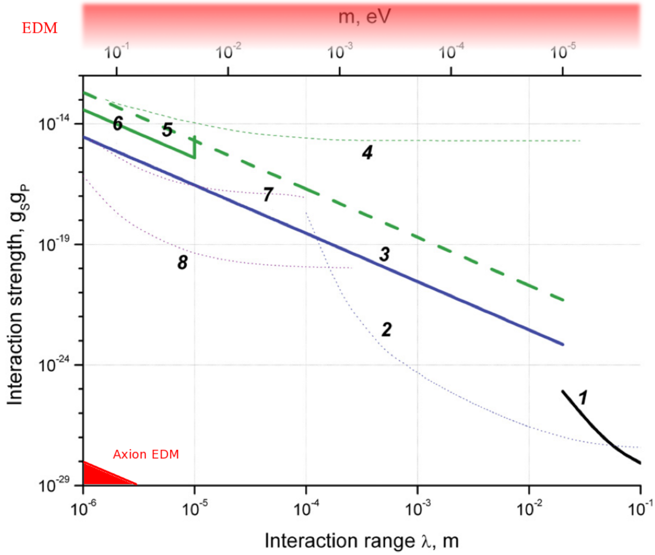
Q-Bounce – Bounds

I. Antoniadis *et al.*, Comptes Rendus Physique **12** (2011) 755.



Q-Bounce – Bounds

I. Antoniadis *et al.*, Comptes Rendus Physique **12** (2011) 755.



Conclusions

"Axion-window"

- $2 \times 10^{-5}\ \mathrm{m} < \lambda < 2 \times 10^{-1}\ \mathrm{m}$
- $10^{-6}\ \mathrm{eV} < m_\varphi < 10^{-2}\ \mathrm{eV}$

EDM constraints **cannot compete** with "fifth-force" experiments

In region

- $10^{-9}\ \mathrm{m} \lesssim \lambda \lesssim 10^{-7}\ \mathrm{m}$
- $1\ \mathrm{eV} \lesssim m_\varphi \lesssim 10^{2}\ \mathrm{eV}$

EDM constraints and "fifth-force" experiments may **pose equal bounds**

Conclusions

In region

- $\lambda \lesssim 10^{-9}$ m
- $m_\varphi \gtrsim 10^2$ eV

EDM constraints supposedly are **more stringent** than "fifth-force" experiments bounds

In the *"axion-window"* the "fifth-force" experiments bounds could be used to **discriminate** between EDM sources by putting **stronger bounds** on the source induced by *scalar particles*

Outlook: nEDM with Dyson-Schwinger Equations

Non-perturbative continuum approach to any **QFT**

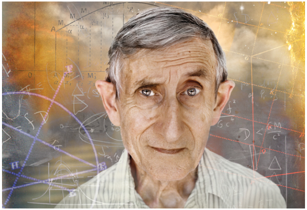
$$\left[-\frac{\delta S}{\delta\bar{\psi}(x)}\left(\frac{\delta}{\delta\bar{\eta}},-\frac{\delta}{\delta\eta},\frac{\delta}{\delta J_{\mu}}\right)+\eta(x)\right]Z[\eta,\bar{\eta},J]=0$$

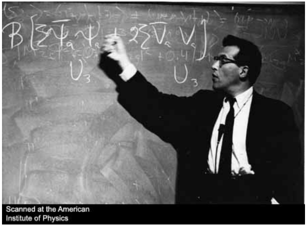
Axions

The **QCD θ-term** for the neutron can be evaluated putting EDM bounds on $g_s g_p$

Scalar w/o PQ Symmetry

Virtual scalar loops with coupling g_s^q and g_p^q between the quarks of the neutron can be evaluated putting EDM bounds on $g_s g_p$





Collaboration

The results, expounded in this talk, were obtained in Collaboration with

- Michael J. Ramsey-Musolf – *UMass Amherst*
- Sonny Mantry – *NWU & ANL*

Thank You For Your Attention!