Time-Reversal-Violating Form Factors of the Deuteron

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August 11th, 2011
DPF 2011, Brown University

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arXiv:1102.4068, to appear in PRL

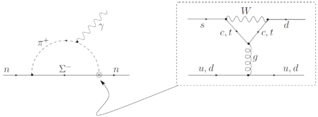
Outline

Motivations and Introduction

A permanent Electric Dipole Moment (EDM) of a particle with spin

- signal of T and P violation
- signal T violation in the flavor diagonal sector
- relatively insensitive to the CKM phase

Standard Model:



$d_n \sim 10^{-19}\ e$ fm

for review: M. Pospelov and A. Ritz, ‘05

Current bounds:

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

  UltraCold Neutron Experiment @ ILL

  C. A. Baker *et al.*, ‘06

- proton $|d_p| < 7.9 \times 10^{-12}\ e$ fm

  ^{199}Hg EDM @ Univ. of Washington

  W. C. Griffith *et al.*, ‘09

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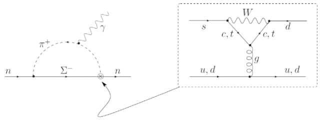

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Large window for new physics and intense experimental activity!

nEDM @ PSI, SNS

pEDM, dEDM @ BNL, COSY

- push d_n to $\sim 10^{-14} - 10^{-15}\, e$ fm
- direct observation of d_p, d_d at $\sim 10^{-16}\, e$ fm

Motivations and Introduction

Can a measurement of nucleon or deuteron EDM pinpoint the microscopic mechanism(s) that generates it?

a. high energy: modelling beyond SM physics — *leave it to model builders*

Y. Li talk in EDM session

b. low energy: hadronic or nuclear matrix element — **non perturbative QCD problem**

Strategy: Chiral symmetry of QCD & low energy Effective Field Theories

different properties under $SU_L(2) \times SU_R(2)$

$$\Downarrow$$

different relations between low-energy TV observables

Can a measurement of nucleon or deuteron EDM pinpoint the microscopic mechanism(s) that generates it?

a. high energy: modelling beyond SM physics *leave it to model builders*

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b. low energy: hadronic or nuclear matrix element **non perturbative QCD problem**

Strategy: Chiral symmetry of QCD & low energy Effective Field Theories

- integrate out all the heavy fields

$$\mathcal{L} = \mathcal{L}_{QCD} + \mathcal{L}_{\not{T}} = \mathcal{L}_{QCD} + \sum_n \frac{c_n}{M_{\not{T}}^{d_n - 4}} \mathcal{O}_{\not{T}\,n}\,(A_\mu, G_\mu, u, d)$$

- construct hadronic operators with same chiral properties as $\mathcal{O}_{\not{T},n}$
- organize operators in a systematic expansion in m_π / M_{QCD}
- hide non perturbative ignorance in (hopefully few) unknown coefficients
- look for qualitatively different low energy effects of various TV sources

The QCD Theta Term

$$\mathcal{L}_4 = -\theta \frac{g_s^2}{32\pi^2} \varepsilon^{\mu\nu\alpha\beta} \mathrm{Tr} G_{\mu\nu} G_{\alpha\beta} - \bar{q}_R M q_L - \bar{q}_L M^* q_R,$$

$$M = \bar{m} e^{i\varphi} \begin{pmatrix} 1-\varepsilon & 0 \\ 0 & 1+\varepsilon \end{pmatrix}$$

$$\bar{m} = (m_u + m_d)/2$$
$$\varepsilon = (m_d - m_u)/(m_d + m_u)$$

- $\theta, \varphi \neq 0$ break P and T
- $M \neq 0$ explicitly breaks chiral symmetry

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- $\theta, \varphi \neq 0$ break P and T
- $M \neq 0$ explicitly breaks chiral symmetry

- eliminate θ with (anomalous) $SU_A(2) \times U_A(1)$ axial rotation

$$\mathcal{L}_4 = -\bar{m}\, r(\bar{\theta})\, \bar{q}q + \varepsilon \bar{m}\, r^{-1}(\bar{\theta})\, \bar{q}\tau_3 \bar{q} + m_\star \, \sin\bar{\theta}\, r^{-1}(\bar{\theta})\, i\bar{q}\gamma^5 q,$$

with

$$\bar{\theta} = 2\varphi - \theta, \qquad m_\star = \frac{m_u m_d}{m_u + m_d} = \frac{\bar{m}}{2}\left(1 - \varepsilon^2\right)$$

The QCD Theta Term

$$\begin{aligned}\mathcal{L}_4 &= -\theta\frac{g_s^2}{32\pi^2}\varepsilon^{\mu\nu\alpha\beta}\mathrm{Tr}G_{\mu\nu}G_{\alpha\beta} - \bar{q}_R M q_L - \bar{q}_L M^* q_R,\\ M &= \bar{m}e^{i\varphi}\begin{pmatrix} 1-\varepsilon & 0 \\ 0 & 1+\varepsilon\end{pmatrix}\end{aligned}$$

$$\begin{gathered}\bar{m} = (m_u + m_d)/2\\ \varepsilon = (m_d - m_u)/(m_d + m_u)\end{gathered}$$

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$$\mathcal{L}_4 = -\bar{m}\, r(\bar{\theta})\, S_4 + \varepsilon\bar{m}\, r^{-1}(\bar{\theta})\, P_3 + m_\star\, \sin\bar{\theta}\, r^{-1}(\bar{\theta})\, P_4,$$

- $\bar{\theta}$ and m break chiral symmetry in a very specific way

$$S = \begin{pmatrix} -i\bar{q}\gamma^5\boldsymbol{\tau}q \\ \bar{q}q \end{pmatrix} \qquad P = \begin{pmatrix} \bar{q}\boldsymbol{\tau}q \\ i\bar{q}\gamma^5 q \end{pmatrix}$$

- $SO(4)$ vector
- $SO(4)$ vector

Dimension 6 TV sources

1. quark EDM (qEDM) and chromo-EDM (qCEDM)

$$\mathcal{L}_{6,\, qq\varphi\mathrm{v}} = -\frac{1}{2}\, \bar{q}\, i\sigma^{\mu\nu}\gamma^5\, (d_0 + d_3\tau_3)\, q\, F_{\mu\nu} - \frac{1}{2}\, \bar{q}\, i\sigma^{\mu\nu}\gamma^5 \left(\tilde{d}_0 + \tilde{d}_3\tau_3\right) \lambda^a q\, G^a_{\mu\nu}$$

2. gluon chromo-EDM (gCEDM)

$$\mathcal{L}_{6,\, \mathrm{ggg}} = \frac{d_W}{6} f^{abc} \varepsilon^{\mu\nu\alpha\beta} G^a_{\alpha\beta} G^b_{\mu\rho} G^{c\,\rho}_{\nu}$$

3. TV Chiral-Invariant (CI) 4-quark operators

$$\mathcal{L}_{6,\, qqqq} = \frac{1}{4} \mathrm{Im}\Sigma_1 \left(\bar{q}q\, \bar{q}i\gamma^5 q - \bar{q}\boldsymbol{\tau} q\, \cdot \bar{q}\boldsymbol{\tau} i\gamma^5 q\right) + \ldots$$

Buchmuller & Wyler ‘86, Weinberg ‘89, de Rujula *et al.* ‘91, . . .

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4th *and* 3rd components of $SO(4)$ vectors

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chiral invariant

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4^{th} *and* 3^{rd} components of $SO(4)$ vectors

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$$\mathcal{L}_{6,\,ggg} = \frac{d_W}{6} f^{abc}\varepsilon^{\mu\nu\alpha\beta}G^a_{\alpha\beta}G^b_{\mu\rho}G^{c\,\rho}_{\nu}$$

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- coefficients:

$$d_i = \mathcal{O}\left(e\delta\frac{\bar{m}}{M^2_{\not T}}\right), \quad \tilde{d}_i = \mathcal{O}\left(4\pi\tilde{\delta}\frac{\bar{m}}{M^2_{\not T}}\right), \quad d_w = \mathcal{O}\left(4\pi\frac{w}{M^2_{\not T}}\right), \quad \Sigma_i = \mathcal{O}\left((4\pi)^2\frac{\sigma}{M^2_{\not T}}\right)$$

- dimensionless factor δ, $\tilde{\delta}$, w and σ depend on details of TV mechanism

The T-Violating Chiral Lagrangian

- spontaneous breaking of $SU_L(2) \times SU_R(2)$

$\Longrightarrow$ separation of scales: $Q, m_\pi \ll M_{QCD} \sim 2\pi F_\pi, m_N$
expansion of $\mathcal{L}_{EFT}$ & amplitudes in Q/M_{QCD}

The T-Violating Chiral Lagrangian

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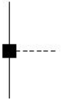
$$\Longrightarrow \text{separation of scales: } Q, m_\pi \ll M_{QCD} \sim 2\pi F_\pi, m_N$$

$$\text{expansion of } \mathcal{L}_{EFT} \text{ \& amplitudes in } Q/M_{QCD}$$

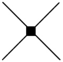
TV Ingredients:

- pion-nucleon TV interactions



$$\mathcal{L}_{\not{T}, f=2} = -\frac{\bar{g}_0}{F_\pi} \bar{N} \boldsymbol{\pi} \cdot \boldsymbol{\tau} N - \frac{\bar{g}_1}{F_\pi} \pi_3 \, \bar{N} N - \frac{\bar{g}_2}{F_\pi} \pi_3 \, \bar{N} \tau_3 N$$

- nucleon-nucleon TV interactions



$$\mathcal{L}_{\not{T}, f=4} \quad = \quad \bar{C}_1 \bar{N} N \partial_\mu (\bar{N} S^\mu N) + \bar{C}_2 \bar{N} \boldsymbol{\tau} N \cdot \mathcal{D}_\mu (\bar{N} \boldsymbol{\tau} S^\mu N)$$

- nucleon-photon TV interactions

$$\mathcal{L}_{\not{T}\gamma, f=2} = 2\bar{N} \left(\bar{D}_0 + \bar{D}_1 \tau_3 \right) S^\mu v^\nu N F_{\mu\nu}$$

Discussion

	pion-nucleon	photon-nucleon $\times\, Q^2$	nucleon-nucleon $\times\, F_\pi^2 Q$
$\bar{\theta}$ term, qCEDM	1	Q^2/M_{QCD}^2	Q^2/M_{QCD}^2
gCEDM 4-quark	1	1	1
qEDM	$\alpha_{\rm em}/\pi$	Q^2/M_{QCD}^2	$\alpha_{\rm em} Q^2/\pi M_{QCD}^2$

- chiral-breaking sources
  TV π-N couplings have lowest chiral index

1. pion loops and short-range EDM operators equally important for nucleon EDM
2. pion-exchange dominate EDMs of light nuclei

...unless selection rules!

	pion-nucleon	photon-nucleon $\times\, Q^2$	nucleon-nucleon $\times\, F_\pi^2 Q$
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- chiral-breaking sources
  TV π-N couplings have lowest chiral index
- chiral-invariant sources
  same chiral index for all interactions

1. short-range EDM operators dominate nucleon EDM
2. one-body effects & pion-exchange at the same level in light nuclei

Discussion

	pion-nucleon	photon-nucleon $\times\ Q^2$	nucleon-nucleon $\times\ F_\pi^2 Q$
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- chiral-breaking sources
  TV π-N couplings have lowest chiral index
- chiral-invariant sources
  same chiral index for all interactions
- qEDM
  long-distance suppressed by $\alpha_{\rm em}$

1. nucleon and nuclei EDMs dominated by TV currents

Discussion

		$\bar{g}_0$	$\bar{g}_1$	$\bar{g}_2$
$\bar{\theta}$ term	LO	$\bar{\theta}$	—	—
	N^{2}LO	$\bar{\theta}\, m_\pi^2/M_{QCD}^2$	$\bar{\theta}\varepsilon\, m_\pi^2/M_{QCD}^2$	—
qCEDM	LO	$\tilde{\delta}$	$\tilde{\delta}$	—
	N^{2}LO	$\tilde{\delta} m_\pi^2/M_{QCD}^2$	$\tilde{\delta} m_\pi^2/M_{QCD}^2$	$\tilde{\delta} m_\pi^2/M_{QCD}^2$
TV CI	LO	w	w	—

$\bar{\theta}$ term

- only isoscalar $\bar{g}_0$ at LO
- isovector $\bar{g}_1$ suppressed by m_π^2/M_{QCD}^2 important for dEDM!

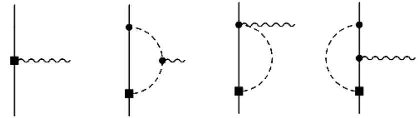
qCEDM

- $\bar{g}_0$ and $\bar{g}_1$ equally important

TV CI sources

- $\bar{g}_1$ and $\bar{g}_0$ equally important
- ... but more derivative & short-distance effects equally relevant

Nucleon EDM. Theta Term & qCEDM



$$J^{\mu}_{ed}(q) = 2\left(S^{\mu} v \cdot q - S \cdot q v^{\mu}\right)\left(F_0(\mathbf{q}^2) + \tau_3 F_1(\mathbf{q}^2)\right), \qquad F_i(\mathbf{q}^2) = D_i - S_i' \mathbf{q}^2 + H_i(\mathbf{q}^2)$$

Theta Term

- F_0 purely short-distance physics. No momentum dependence

$$D_0 = \bar{D}_0^{(3)}, \qquad S_0' = 0.$$

- F_1 sensitive to short-distance & charged pions in loop   only $\bar{g}_0$ contributes!

$$D_1 = \bar{D}_1^{(3)} + \frac{e g_A \bar{g}_0}{m_\pi^2} \frac{m_\pi^2}{(2\pi F_\pi)^2}\left[L - \ln\frac{m_\pi^2}{\mu^2}\right], \qquad S_1' = \frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2}\frac{1}{6 m_\pi^2}.$$

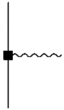
qCEDM

- $\bar{g}_1$ irrelevant
- power counting relations between $\bar{g}_0, \bar{D}_{0,1}$ same as for Theta Term,

$$\boxed{\text{Theta Term and qCEDM give identical nucleon EDFF}}$$

true to NLO

Nucleon EDM and EDFF. qEDM & TV CI sources



- EDFF purely short-distance & momentum independent at LO

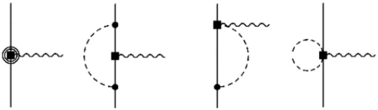
- isoscalar

$$F_0(\mathbf{q}^2) = D_0 = \bar{D}_0^{(n)}, \qquad S_0' = 0$$

- isovector

$$F_1(\mathbf{q}^2) = D_1 = \bar{D}_1^{(n)}, \quad S_1' = 0.$$

Nucleon EDM and EDFF. qEDM & TV CI sources



- EDFF purely short-distance & momentum independent at LO
- EDFF acquires momentum dependence at NNLO
  - purely short distance for qEDM
  - with long distance component for TV CI sources
- isoscalar

$$D_0 = \bar{D}_0^{(n)} + \bar{\bar{D}}_0^{(n+2)}, \quad S_0' = \bar{S}_0'^{(n+2)}$$

- isovector

$$D_1 = \bar{D}_1^{(n)} + \bar{\bar{D}}_1^{(n+2)}, \quad S_1' = \bar{S}_1'^{(n+2)}$$

Nucleon EDM and EDFF. Sum up

Source	$\bar{\theta}$	qCEDM	qEDM	TV CI
$M_{\mathrm{QCD}}\, d_n/e$	$\mathcal{O}\left(\bar{\theta}\,\frac{m_\pi^2}{M_{\mathrm{QCD}}^2}\right)$	$\mathcal{O}\left(\tilde{\delta}\,\frac{m_\pi^2}{M_{\not T}^2}\right)$	$\mathcal{O}\left(\delta\,\frac{m_\pi^2}{M_{\not T}^2}\right)$	$\mathcal{O}\left(w\,\frac{M_{\mathrm{QCD}}^2}{M_{\not T}^2}\right)$
d_p/d_n	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$m_\pi^2 S_1'/d_n$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{\mathrm{QCD}}^2}\right)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{\mathrm{QCD}}^2}\right)$
$m_\pi^2 S_0'/d_n$	$\mathcal{O}\left(\frac{m_\pi}{M_{\mathrm{QCD}}}\right)$	$\mathcal{O}\left(\frac{m_\pi}{M_{\mathrm{QCD}}}\right)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{\mathrm{QCD}}^2}\right)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{\mathrm{QCD}}^2}\right)$

- measurement of d_n and d_p can be fitted by any source.
  No signal @ PSI, SNS:

$$\bar{\theta} \lesssim 10^{-12}, \qquad \frac{\tilde{\delta}, \delta}{M_{\not T}^2} \lesssim (10^3\ \mathrm{TeV})^{-2}, \qquad \frac{w}{M_{\not T}^2} \lesssim (5 \cdot 10^3\ \mathrm{TeV})^{-2}$$

- S_1' come at the same order as D_i
- S_0' suppressed by m_π/M_{QCD} with respect to D_i
- scale for momentum variation of EDFF set by m_π

Theta Term & qCEDM

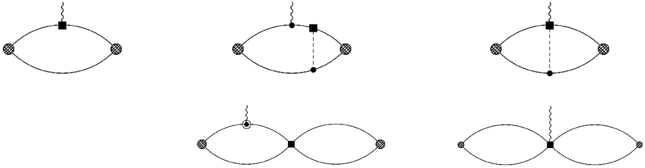
- $S_{1,0}'$ suppressed by m_π^2/M_{QCD}^2 with respect to D_i

qEDM & TV CI

Deuteron EDM and MQM

Spin 1 particle

$$H_{\not{T}} = -2d_d\mathcal{D}^\dagger \mathbf{S}\cdot\mathbf{E}\mathcal{D} - \frac{\mathcal{M}_d}{2}\mathcal{D}_j^\dagger \mathcal{D}_i \nabla^{(i}B^{j)}$$



- One-body
- TV wavefunction
- TV currents

Perturbative pion EFT

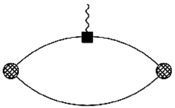
- expansion in powers of Q/M_{QCD}
- **and** γ/M_{NN}

$\gamma = \sqrt{m_N B} \sim 45$ MeV deuteron binding momentum
$M_{NN} = 4\pi F_\pi^2/m_N \sim 350$ MeV nuclear scale

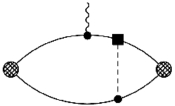
- γ only relevant deuteron parameter at LO

Deuteron EDM

One-body



TV corrections to wavefunction



- only sensitive to isoscalar nucleon EDM

$$F_D(\mathbf{q}^2) = 2D_0 \frac{4\gamma}{|\mathbf{q}|} \arctan\left(\frac{|\mathbf{q}|}{4\gamma}\right) = 2D_0 \left(1 - \frac{1}{3}\left(\frac{|\mathbf{q}|}{4\gamma}\right)^2 + \dots\right)$$

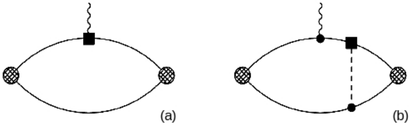
- sensitive to **isobreaking** $\bar{g}_1$

$$F_D(\mathbf{q}^2) = -\frac{2}{3} e \frac{g_A \bar{g}_1}{m_\pi^2} \frac{m_N m_\pi}{4\pi F_\pi^2} \frac{1+\xi}{(1+2\xi)^2} \left(1 - 0.45\left(\frac{|\mathbf{q}|}{4\gamma}\right)^2 + \dots\right), \qquad \xi = \frac{\gamma}{m_\pi}$$

- relative size different for different sources!

Deuteron EDM. qCEDM

qCEDM: chiral breaking & isospin breaking



$$d_d = 2D_0 - \frac{2}{3} e \frac{g_A \bar{g}_1}{m_\pi^2} \frac{m_N m_\pi}{4\pi F_\pi^2} \frac{1+\xi}{(1+2\xi)^2}$$

$$\mathcal{O}\left(\frac{\tilde{\delta}}{M_{\not T}^2} \frac{m_\pi^2}{M_{QCD}}\right) \qquad \mathcal{O}\left(\frac{\tilde{\delta}}{M_{\not T}^2} \frac{M_{QCD} m_\pi}{M_{NN}}\right)$$

deuteron EDM enhanced w.r.t. nucleon!

- $\bar{g}_1$ leading interaction
- D_0 suppressed by two powers of M_{QCD}

$$\frac{d_d}{d_n} \sim \frac{M_{QCD}^2}{m_\pi M_{NN}} \sim 10$$

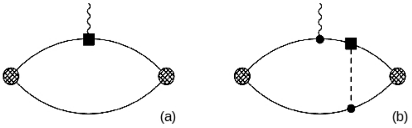
Deuteron EDM. Theta Term & TV CI Sources

Theta term: chiral breaking & isospin symmetric

TV CI Sources: chiral invariant

$\bar{g}_1$ suppressed!

D_0 enhanced!



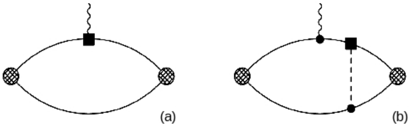
$$d_d = 2D_0 - \frac{2}{3} e \frac{g_A \bar{g}_1}{m_\pi^2} \frac{m_N m_\pi}{4\pi F_\pi^2} \frac{1+\xi}{(1+2\xi)^2}$$

$$\mathcal{O}\left(\bar{\theta} \frac{m_\pi^2}{M_{QCD}^3}\right) \qquad \mathcal{O}\left(\bar{\theta}\varepsilon \frac{m_\pi^2}{M_{QCD}^3} \frac{m_\pi}{M_{NN}}\right)$$

- $\bar{g}_1$ & D_0 appear at the same level in the Lagrangian
- dEDM well approximated by $d_n + d_p$

Deuteron EDM. qEDM

qEDM: $\pi - N$ coupling suppressed by $\alpha_{\rm em}$



$$d_d = 2D_0 - \frac{2}{3} e \frac{g_A \bar{g}_1}{m_\pi^2} \frac{m_N m_\pi}{4\pi F_\pi^2} \frac{1+\xi}{(1+2\xi)^2}$$

$$\mathcal{O}\left(\frac{\delta}{M_{\not T}^2} \frac{m_\pi^2}{M_{QCD}}\right)$$

- dEDM well approximated by $d_n + d_p$

Deuteron EDM. Summary

Source	$\bar{\theta}$	qCEDM	qEDM	TV CI
$M_{QCD}\, d_d/e$	$\mathcal{O}\left(\bar{\theta}\,\frac{m_\pi^2}{M_{QCD}^2}\right)$	$\mathcal{O}\left(\tilde{\delta}\,\frac{m_\pi M_{QCD}^2}{M_{NN} M_{\not T}^2}\right)$	$\mathcal{O}\left(\delta\,\frac{m_\pi^2}{M_{\not T}^2}\right)$	$\mathcal{O}\left(w\,\frac{M_{QCD}^2}{M_{\not T}^2}\right)$
d_d/d_n	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{M_{QCD}^2}{m_\pi M_{NN}}\right)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$

- deuteron EDM signal can be fitted by any source
- deuteron EDM well approximated by $d_n + d_p$ for $\bar{\theta}$, qEDM and TV CI sources
- only for qCEDM, $d_d \gg d_n + d_p$

qCEDM

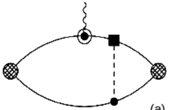
- deuteron EDM experiment more sensitive than neutron & proton EDM

$$d_d \lesssim 10^{-16}\, e\,\mathrm{fm} \Longrightarrow \frac{\tilde{\delta}}{M_{\not T}^2} \lesssim (3 \cdot 10^4\,\mathrm{TeV})^{-2}$$

- nucleon and deuteron EDM *qualitatively* pinpoint qCEDM.

Deuteron MQM. Chiral Breaking Sources

Corrections to wavefunction



(a)

$$m_d \mathcal{M}_d = 2e \frac{g_A \bar{g}_0}{m_\pi^2} \frac{m_N m_\pi}{2\pi F_\pi^2} \left[(1+\kappa_0) + \frac{\bar{g}_1}{3\bar{g}_0}(1+\kappa_1) \right] \frac{1+\xi}{(1+2\xi)^2},$$

qCEDM

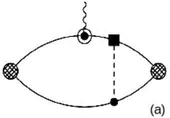
- $\bar{g}_0$ and $\bar{g}_1$ equally important
- dEDM and dMQM comparable

$$\left| \frac{m_d \mathcal{M}_d}{2 d_d} \right| = (1+\kappa_1) + \frac{3\bar{g}_0}{\bar{g}_1}(1+\kappa_0)$$

ratio independent of deuteron details!

Deuteron MQM. Chiral Breaking Sources

Corrections to wavefunction



$$m_d \mathcal{M}_d \quad = \quad 2e \frac{g_A \bar{g}_0}{m_\pi^2} \frac{m_N m_\pi}{2\pi F_\pi^2} (1+\kappa_0) \frac{1+\xi}{(1+2\xi)^2},$$

Theta Term

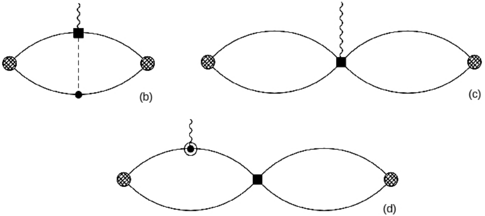
- only $\bar{g}_0$ contributes
- dMQM bigger than dEDM

$$\left| \frac{m_d \mathcal{M}_d}{d_d} \right| = \frac{2}{3} (1+\kappa_0) \frac{1+\xi}{(1+2\xi)} \left(\frac{m_N}{m_\pi} \right)^2 \lesssim 12$$

using largest non-analytic contribution to D_0 to estimate d_d.

Deuteron MQM. qEDM & TV CI Sources

Corrections to wavefunction + TV currents



- new two-body low-energy constants

loss of predictive power!

- for both sources $m_d \mathcal{M}_d \lesssim d_d$

no useful new info from observation of dMQM

Deuteron EDM & MQM. Summary

Source	$\bar\theta$	qCEDM	qEDM	TV CI
$M_{QCD}\, d_d/e$	$\mathcal{O}\left(\bar\theta \frac{m_\pi^2}{M_{QCD}^2}\right)$	$\mathcal{O}\left(\tilde\delta \frac{m_\pi M_{QCD}^2}{M_{NN} M_{\not T}^2}\right)$	$\mathcal{O}\left(\delta \frac{m_\pi^2}{M_{\not T}^2}\right)$	$\mathcal{O}\left(w \frac{M_{QCD}^2}{M_{\not T}^2}\right)$
d_d/d_n	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{M_{QCD}^2}{m_\pi M_{NN}}\right)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$m_d \mathcal{M}_d/d_d$	$\mathcal{O}\left(\frac{M_{QCD}^2}{m_\pi M_{NN}}\right)$	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{m_\pi}{M_{NN}}\right)$	$\mathcal{O}(1)$

qCEDM

- deuteron EDM experiment more sensitive than neutron & proton EDM

$$d_d \lesssim 10^{-16}\, e\,\mathrm{fm} \Longrightarrow \frac{\tilde\delta}{M_{\not T}^2} \lesssim (3\cdot 10^4\,\mathrm{TeV})^{-2}$$

- nucleon and deuteron EDM *qualitatively* pinpoint qCEDM.
- *quantitatively* $\Longrightarrow$ need for deuteron MQM and nucleon EDFF momentum dependence

$$\left|\frac{m_d \mathcal{M}_d}{2 d_d}\right| = (1+\kappa_1) + \frac{3\bar g_0}{\bar g_1}(1+\kappa_0)$$

prediction! *if* $\bar g_0$ extracted from nucleon EDFF, $\bar g_1$ from deuteron EDM.

Explore ^{3}He EDM for extraction of $\bar g_0$!

Deuteron EDM & MQM. Summary

Source	$\bar{\theta}$	qCEDM	qEDM	TV CI
$M_{QCD}\, d_d/e$	$\mathcal{O}\left(\bar{\theta}\,\frac{m_\pi^2}{M_{QCD}^2}\right)$	$\mathcal{O}\left(\tilde{\delta}\,\frac{m_\pi M_{QCD}^2}{M_{NN} M_{\not{T}}^2}\right)$	$\mathcal{O}\left(\delta\,\frac{m_\pi^2}{M_{\not{T}}^2}\right)$	$\mathcal{O}\left(w\,\frac{M_{QCD}^2}{M_{\not{T}}^2}\right)$
d_d/d_n	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{M_{QCD}^2}{m_\pi M_{NN}}\right)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$m_d \mathcal{M}_d/d_d$	$\mathcal{O}\left(\frac{M_{QCD}^2}{m_\pi M_{NN}}\right)$	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{m_\pi}{M_{NN}}\right)$	$\mathcal{O}(1)$

Theta Term

- Nucleon EDM and deuteron MQM *qualitatively* pinpoint Theta Term
- *quantitatively* $\Longrightarrow$ one more observable!

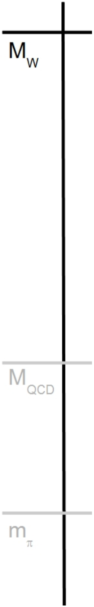
nucleon EDFF momentum dependence
^{3}He EDM

qEDM & TV CI Sources

- no relevant new info from deuteron EDM and MQM

Backup Slides

Dimension 6 TV sources



- no dimension 5 operator with quarks/gluons
- **dimension 6**

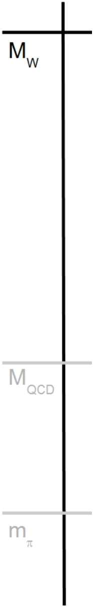
$$
\begin{aligned}
\mathcal{L}_{6,\,\mathrm{ggg}} &= \frac{d_W}{6} f^{abc} \varepsilon^{\mu\nu\alpha\beta} G^a_{\alpha\beta} G^b_{\mu\rho} G^{c\ \rho}_{\nu} \\
\mathcal{L}_{6,\,qq\varphi\mathrm{v}} &= -\frac{1}{\sqrt{2}} \bar{q}_L \sigma^{\mu\nu} \tilde{\Gamma}^u \lambda^a \frac{\tilde{\varphi}}{v} u_R G^a_{\mu\nu} - \frac{1}{\sqrt{2}} \bar{q}_L \sigma^{\mu\nu} \tilde{\Gamma}^d \lambda^a \frac{\varphi}{v} d_R G^a_{\mu\nu} \\
&\quad -\frac{1}{\sqrt{2}} \bar{q}_L \sigma^{\mu\nu} \left(\Gamma^u_B B_{\mu\nu} + \Gamma^u_W \boldsymbol{\tau} \cdot \mathbf{W}_{\mu\nu} \right) \frac{\tilde{\varphi}}{v} u_R + \dots \\
\mathcal{L}_{6,\,qqqq} &= \Sigma_1 \left(\bar{q}^J_L u_R \right) \varepsilon_{JK} \left(\bar{q}^K_L d_R \right) + \Sigma_8 \left(\bar{q}^J_L \lambda^a u_R \right) \varepsilon_{JK} \left(\bar{q}^K_L \lambda^a d_R \right) + \mathrm{h.c.}
\end{aligned}
$$

Buchmuller & Wyler ‘86, Weinberg ‘89, de Rujula *et al.* ‘91, . . .

- Γ and Σ complex-valued matrices in flavor space

$$
d_W = \mathcal{O}\left(4\pi \frac{w}{M_{\not{T}}^2}\right), \quad \tilde{\Gamma}^{u,d} = \mathcal{O}\left(4\pi \tilde{\delta}_{u,d} \frac{v \lambda_{u,d}}{M_{\not{T}}^2}\right), \quad \Sigma_{1,8} = \mathcal{O}\left((4\pi)^2 \frac{\sigma_{1,8}}{M_{\not{T}}^2}\right)
$$

Dimension 6 TV sources



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&\quad - \frac{1}{\sqrt{2}} \bar{q}_L \sigma^{\mu\nu} \left(\Gamma^u_B B_{\mu\nu} + \Gamma^u_W \boldsymbol{\tau} \cdot \mathbf{W}_{\mu\nu} \right) \frac{\tilde{\varphi}}{v} u_R + \dots \\
\mathcal{L}_{6,\,qqqq} &= \Sigma_1 \left(\bar{q}^J_L u_R \right) \varepsilon_{JK} \left(\bar{q}^K_L d_R \right) + \Sigma_8 \left(\bar{q}^J_L \lambda^a u_R \right) \varepsilon_{JK} \left(\bar{q}^K_L \lambda^a d_R \right) + \mathrm{h.c.}
\end{aligned}
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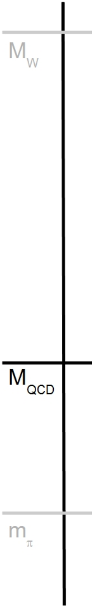
$$
d_W = \mathcal{O}\left(4\pi \frac{w}{M^2_{\not{T}}} \right), \quad \tilde{\Gamma}^{u,d} = \mathcal{O}\left(4\pi \tilde{\delta}_{u,d} \frac{v \lambda_{u,d}}{M^2_{\not{T}}} \right), \quad \Sigma_{1,8} = \mathcal{O}\left((4\pi)^2 \frac{\sigma_{1,8}}{M^2_{\not{T}}} \right)
$$

Dimension 6 TV sources



1. spontaneous symmetry breaking: $\varphi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$
2. integrate out heavy stuff (c, b, t, W, Z, Higgs)

- gluon chromo-EDM (gCEDM)

$$\mathcal{L}_{6,\,\mathrm{ggg}} = \frac{d_W}{6} f^{abc} \varepsilon^{\mu\nu\alpha\beta} G^a_{\alpha\beta} G^b_{\mu\rho} G^{c\;\rho}_{\nu}$$

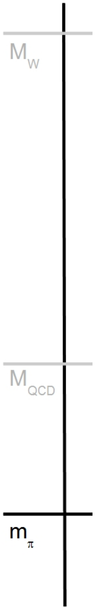
- quark EDM (qEDM) and chromo-EDM (qCEDM)

$$\mathcal{L}_{6,\,qq\varphi\mathrm{v}} = -\frac{1}{2}\,\bar{q}\, i\sigma^{\mu\nu}\gamma^5\,(d_0 + d_3\tau_3)\,q\,F_{\mu\nu} - \frac{1}{2}\,\bar{q}\, i\sigma^{\mu\nu}\gamma^5 \left(\tilde{d}_0 + \tilde{d}_3\tau_3\right) \lambda^a q\, G^a_{\mu\nu}$$

- TV Chiral Invariant (CI) 4-quark operators

$$\mathcal{L}_{6,\,qqqq} = \frac{1}{4}\mathrm{Im}\Sigma_1 \left(\bar{q}q\,\bar{q}i\gamma^5 q - \bar{q}\boldsymbol{\tau}q \cdot \bar{q}\boldsymbol{\tau}i\gamma^5 q\right) + \ldots$$

Chiral properties of dimension 6 sources



1. qCEDM & qEDM

$$\mathcal{L}_{qq\varphi v} = -\tilde{d}_0 \tilde{V}_4 + \tilde{d}_3 \tilde{W}_3 - d_0 V_4 + d_3 W_3$$

- $\tilde{V}$, $\tilde{W}$ and V, W $SO(4)$ vectors

2. gCEDM & TV 4-quark operators

$$\mathcal{L}_{ggg} + \mathcal{L}_{qqqq} = d_W I_W + \mathrm{Im}\Sigma_1\, I^{(1)}_{qq} + \mathrm{Im}\Sigma_8\, I^{(8)}_{qq}$$

- I_W, $I^{(1)}_{qq}$, $I^{(8)}_{qq}$ chiral invariant

Coefficients

$$d_{0,3} = \mathcal{O}\left(e\delta \frac{\bar{m}}{M^2_{\not T}}\right), \qquad \tilde{d}_{0,3} = \mathcal{O}\left(4\pi\tilde{\delta}\frac{\bar{m}}{M^2_{\not T}}\right),$$

$$d_w = \mathcal{O}\left(4\pi \frac{w}{M^2_{\not T}}\right), \qquad \Sigma_{1,8} = \mathcal{O}\left((4\pi)^2 \frac{\sigma}{M^2_{\not T}}\right)$$

- dimensionless factor δ, $\tilde{\delta}$, w and σ depend on details of TV mechanism

Dimension 6 TV sources

$$
d_{0,3} = \mathcal{O}\left(e\delta \frac{\bar{m}}{M_{\not T}^2}\right), \qquad \tilde{d}_{0,3} = \mathcal{O}\left(4\pi\tilde{\delta} \frac{\bar{m}}{M_{\not T}^2}\right),
$$

$$
d_w = \mathcal{O}\left(4\pi \frac{w}{M_{\not T}^2}\right), \qquad \Sigma_{1,8} = \mathcal{O}\left((4\pi)^2 \frac{\sigma}{M_{\not T}^2}\right)
$$

- dimensionless factor δ, $\tilde{\delta}$, w and σ depend on details of TV mechanism

1. **Naturalness**

$$
\delta = \mathcal{O}(1), \qquad \tilde{\delta} = \mathcal{O}\left(\frac{g_s}{4\pi}\right), \qquad w = \mathcal{O}\left(\frac{g_s^3}{(4\pi)^3}\right), \qquad \sigma = \mathcal{O}(1)
$$

2. **Standard Model**

- $M_{\not T} = M_W$

$$
\delta \sim J_{\mathrm{CP}} \frac{m_{c,s}^2}{M_W^2} \qquad\qquad w \sim \frac{g_s^3}{(4\pi)^3} J_{\mathrm{CP}} \frac{m_b^2 m_c^2 m_s^2}{M_W^6}
$$

M. Pospelov and A. Ritz, Ann. Phys. **318**, 119 (2005)

- suppressed by extra powers of M_W!

Dimension 6 TV sources

3. **MSSM**

- $M_{\not{T}} = \tilde{m} \sim \text{TeV}$
- gluino contribution (under various simplifying assumptions)

$$\tilde{\delta} \sim \frac{g_s}{4\pi}\frac{\alpha_s(\tilde{m})}{4\pi}\mathrm{Im}\frac{X_q}{\tilde{m}} \qquad \delta \sim \frac{4}{3}e\frac{\alpha_s(\tilde{m})}{4\pi}\mathrm{Im}\frac{X_q}{\tilde{m}} \qquad w \sim \frac{g_s^3}{(4\pi)^3}\frac{\alpha_s(\tilde{m})}{4\pi}\mathrm{Im}\frac{X_q}{\tilde{m}}$$

T. Ibrahim and P. Nath, Rev. Mod. Phys. **80**, 577 (2008)

- suppressed by $\alpha_s(\tilde{m})$
- σ not studied much. In most models, extra $m_q/M_{\not{T}}$ suppression.

Factors δ, $\tilde{\delta}$, w, σ

- make it difficult to compare *different* dim. 6 sources in a way independent of new physics model
- for *each* source, chiral expansion allows to study *relative* contributions to different TV observables

Electromagnetic and TV operators

- chiral properties of $(P_3 + P_4) \otimes (I + T_{34})$
- lowest chiral order $\Delta = 3$
- $P_3 + P_4$

$$\mathcal{L}^{(3)}_{\not{\chi},f=2,\text{em}} = c^{(3)}_{1,\text{em}} \frac{1}{D} \left[\frac{2\pi_3}{F_\pi} + \rho \left(1 - \frac{\boldsymbol{\pi}^2}{F_\pi^2} \right) \right] \bar{N} \left(S^\mu v^\nu - S^\nu v^\mu \right) N \, eF_{\mu\nu}$$

- $(P_3 + P_4) \otimes T_{34}$

$$\mathcal{L}^{(3)}_{\not{\chi},f=2,\text{em}} = c^{(3)}_{3,\text{em}} \bar{N} \left[-\frac{2}{F_\pi D} \boldsymbol{\pi} \cdot \mathbf{t} - \rho \left(t_3 - \frac{2\pi_3}{F_\pi^2 D} \boldsymbol{\pi} \cdot \mathbf{t} \right) \right] \left(S^\mu v^\nu - S^\nu v^\mu \right) N \, eF_{\mu\nu}$$
$$+ \text{tensor}$$

- isoscalar and isovector EDM related to pion photo-production.

Electromagnetic and TV operators

At the same order $S_4 \otimes (1 + T_{34})$

- S_4

$$\mathcal{L}^{(3)}_{\not{\chi}, f=2,\mathrm{em}} = c^{(3)}_{6,\mathrm{em}} \left(- \frac{2}{F_\pi D} \right) \bar{N} \boldsymbol{\pi} \cdot \mathbf{t} \, (S^\mu v^\nu - S^\nu v^\mu) \, N \, eF_{\mu\nu}$$

- $S_4 \otimes T_{34}$

$$\mathcal{L}^{(3)}_{\not{\chi}, f=2,\mathrm{em}} = c^{(3)}_{8,\mathrm{em}} \frac{2\pi_3}{F_\pi D} \bar{N} \, (S^\mu v^\nu - S^\nu v^\mu) \, N \, eF_{\mu\nu} + \text{tensor}$$

- same chiral properties as partners of TV operator
- pion-photoproduction constrains only $c^{(3)}_{1,\,\mathrm{em}} + c^{(3)}_{6,\,\mathrm{em}}$ and $c^{(3)}_{3,\,\mathrm{em}} + c^{(3)}_{8,\,\mathrm{em}}$
- but TV only depends on $c^{(3)}_{1,\,\mathrm{em}}$ and $c^{(3)}_{3,\,\mathrm{em}}$

no T-conserving observable constrains short distance contrib. to nucleon EDM

- true only in $SU(2) \times SU(2)$
- larger symmetry of $SU(3) \times SU(3)$ leaves question open

Deuteron EDM and MQM. KSW Power Counting

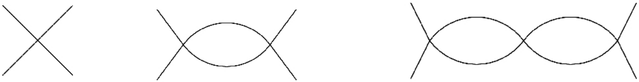
T-even sector

$$\mathcal{L}_{f=4} = -C_0^{^3S_1}(N^tP^iN)^\dagger N^tP^iN + \frac{C_2^{^3S_1}}{8}\left[(N^tP_iN)^\dagger N^t\mathbf{D}_-^2 P_iN + \text{h.c.}\right] + \ldots, \qquad P^i = \frac{1}{\sqrt{8}}\sigma_2\sigma_i\tau_2$$

- enhance C_0 to account for unnaturaly large scattering lengths. In PDS scheme

$$C_0^{^3S_1} = \mathcal{O}\left(\frac{4\pi}{m_N\mu}\right), \qquad \mu \sim Q$$

- iterate C_0 at all orders



C_0 $\qquad$ $C_0\,\frac{m_NQ}{4\pi}C_0$ $\qquad$ $C_0\left(\frac{m_NQ}{4\pi}C_0\right)^2$

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$$\mathcal{L}_{f=4} = -C_0^{^3S_1}(N^tP^iN)^\dagger N^tP^iN + \frac{C_2^{^3S_1}}{8}\left[(N^tP_iN)^\dagger N^t\mathbf{D}_-^2P_iN + \text{h.c.}\right] + \ldots, \qquad P^i = \frac{1}{\sqrt{8}}\sigma_2\sigma_i\tau_2$$

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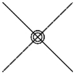
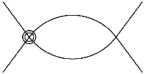
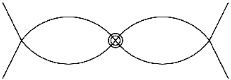
$$C_0^{^3S_1} = \mathcal{O}\left(\frac{4\pi}{m_N\mu}\right), \qquad \mu \sim Q$$

- iterate C_0 at all orders
- operators which connect S-waves get enhanced $C_2^{^3S_1} = \mathcal{O}\left(\frac{4\pi}{m_NM_{NN}}\frac{1}{\mu^2}\right)$



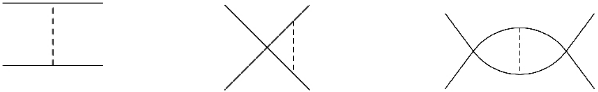




$C_0\,\frac{Q}{M_{NN}}$ $\qquad$ $C_0\,\frac{Q}{M_{NN}}\,\frac{m_NQ}{4\pi}C_0$ $\qquad$ $C_0\,\frac{Q}{M_{NN}}\left(\frac{m_NQ}{4\pi}C_0\right)^2$

Deuteron EDM and MQM. KSW Power Counting

- treat pion exchange as a perturbation



$$C_0 \frac{g_A^2 m_N Q}{4\pi F_\pi^2} \qquad C_0 \frac{g_A^2 m_N Q}{4\pi F_\pi^2} \frac{m_N Q}{4\pi} C_0 \qquad C_0 \frac{g_A^2 m_N Q}{4\pi F_\pi^2} \left(\frac{m_N Q}{4\pi} C_0 \right)^2$$

- identify $M_{NN} = 4\pi F_\pi^2 / m_N \sim 300$ MeV.

Perturbative pion approach:

- expansion in Q/M_{NN}, with $Q \in \{|\mathbf{q}|, m_\pi, \gamma = \sqrt{m_N B}\}$
- competing with the m_π / M_{QCD} of ChPT Lagrangian

- successful for deuteron properties at low energies

Kaplan, Savage and Wise, Phys. Rev. C **59**, 617 (1999);

- problems in ${}^3S_1$ scattering lenghts,
  ptb. series does not converge for $Q \sim m_\pi$

Fleming, Mehen, and Stewart, Nucl. Phys. **A 677**, 313 (2000);

Deuteron EDM and MQM. KSW Power Counting

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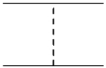
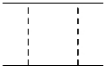


$$\frac{g_A^2}{F_\pi^2}$$



$$\frac{g_A^2}{F_\pi^2}\,\frac{g_A^2 m_N Q}{4\pi F_\pi^2}$$

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- problems in $^3S_1$ scattering lenghts,
  ptb. series does not converge for $Q \sim m_\pi$

  Fleming, Mehen, and Stewart, Nucl. Phys. **A 677**, 313 (2000);

Deuteron EDM and MQM. KSW Power Counting

T-odd sector

a. four-nucleon T-odd operators

$$\mathcal{L}_{\not T, f=4} = C_{1,\not T}\bar{N}S\cdot(\mathcal{D}+\mathcal{D}^{\dagger})N\,\bar{N}N + C_{2,\not T}\bar{N}\boldsymbol{\tau}\,S\cdot(\mathcal{D}+\mathcal{D}^{\dagger})N\ \cdot\bar{N}\,\boldsymbol{\tau}N.$$

- in the PDS scheme

	1. Theta	2. qCEDM	3. qEDM	4. gCEDM
$C_{i,\not T}$	$\frac{4\pi}{\mu m_N}\bar{\theta}\frac{m_\pi^2}{M_{QCD}M_{NN}^2}$	$\frac{4\pi}{\mu m_N}\tilde{\delta}\frac{m_\pi^2}{M_{\not T}^2 M_{QCD}}$	0	$\frac{4\pi}{\mu m_N}\frac{w}{M_{\not T}^2}M_{NN}$

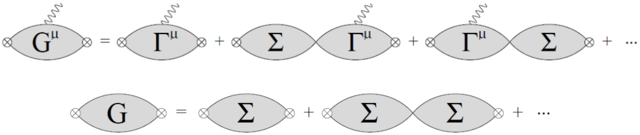
b. four-nucleon T-odd currents

$$\mathcal{L}_{\not T,\,\mathrm{em}, f=4} = C_{1,\not T,\,\mathrm{em}}\bar{N}(S^{\mu}v^{\nu} - S^{\nu}v^{\mu})N\bar{N}NF_{\mu\nu}.$$

- in the PDS scheme

	1. Theta	2. qCEDM	3. qEDM	4. gCEDM
$C_{i,\not T,\mathrm{em}}$	$\frac{4\pi}{\mu^2 m_N}\bar{\theta}\frac{m_\pi^2}{M_{QCD}M_{NN}^2}$	$\frac{4\pi}{\mu^2 m_N}\tilde{\delta}\frac{m_\pi^2}{M_{\not T}^2 M_{QCD}}$	$\frac{4\pi}{\mu^2 m_N}\delta\frac{m_\pi^2}{M_{\not T}^2 M_{QCD}}$	$\frac{4\pi}{\mu^2 m_N}\frac{w}{M_{\not T}^2}M_{NN}$

Deuteron EDM. Formalism



- crossed blob: insertion of interpolating field $\mathcal{D}^i(x) = N(x) P_i^{{}^3S_1} N(x)$
- two-point and three-point Green's functions expressed in terms of *irreducible* function

irreducible: do not contain $C_0^{{}^3S_1}$

- by LSZ formula

$$\langle \mathbf{p}' j | J^{\mu}_{\mathrm{em}, \mathcal{T}} | \mathbf{p}\, i \rangle = i \left[\frac{\Gamma^{\mu}_{ij}(\bar{E}, \bar{E}', \mathbf{q})}{d\Sigma(\bar{E})/dE} \right]_{\bar{E}, \bar{E}' = -B}$$

- two-point function

$$\left. \frac{d\Sigma_{(1)}}{d\bar{E}} \right|_{\bar{E} = -B} = -i \frac{m_N^2}{8\pi\gamma}$$