T violation in nuclear systems. An effective approach

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Outline

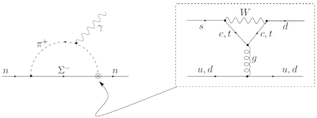
1. Motivations
2. Sources of T violation
3. Chiral Perturbation Theory Lagrangian with T violation
4. Nucleon EDM
5. Deuteron EDM and MQM
6. Triton and Helion EDM
7. Summary & Conclusion

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:



$d_n \sim 10^{-32}\ e$ cm

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

Current bounds:

- neutron $|d_n| < 2.9 \times 10^{-26}\ e$ cm

  UltraCold Neutron Experiment @ ILL

  C. A. Baker *et al.*, '06

- proton $|d_p| < 7.9 \times 10^{-25}\ e$ cm

  ^{199}Hg EDM @ Univ. of Washington

  W. C. Griffith *et al.*, '09

Large window for new physics and intense experimental activity!

T-violating observables

1. Neutron EDM

   UltraCold Neutron experiment @ PSI

- currently taking data
- 2013: $d_n \sim 5 \times 10^{-27}$ e cm
- 2016: $d_n \sim 5 \times 10^{-28}$ e cm

UCN experiment @ SNS Oak Ridge

- 2020: $d_n \sim 10^{-28} e$ cm

T-violating observables

2. Proton EDM

   Storage Ring Experiment @ BNL

- 2010-2013: R&D
- 2013: start ring construction
- 2016: start physics run
  aim for $d_p \sim 10^{-29}$ e cm

3. Deuteron, Triton, Helion EDM

   Storage Ring Experiment @

   ? COSY Jülich Forschungszentrum

   ? BNL, after completion proton EDM

- same sensitivity as proton EDM experiment, $d_d \sim 10^{-29} e$ cm
- no definitive timeline for EDM experiment

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*
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

Motivations and Introduction

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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

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

$$M = \bar{m} e^{i\varphi} \begin{pmatrix} 1-\varepsilon & 0 \\ 0 & 1+\varepsilon \end{pmatrix} \qquad \begin{array}{r} \bar{m} = (m_u + m_d)/2 \\ \varepsilon = (m_d - m_u)/(m_d + m_u) \end{array}$$

- $\theta, \varphi \neq 0$ 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

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

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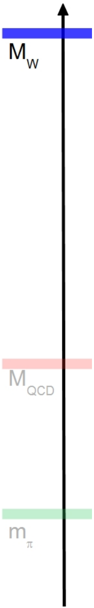
- eliminate θ with (anomalous) $SU_A(2) \times U_A(1)$ axial rotation

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

- $\bar{\theta}$ 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

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

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

$$\mathcal{L}_{6,\,qq\varphi\mathrm{v}} = -\frac{1}{\sqrt{2}} \bar{q}_L \sigma^{\mu\nu} \left\{ \tilde{\Gamma}^u \lambda^a G^a_{\mu\nu} + \Gamma^u_B B_{\mu\nu} + \Gamma^u_W \boldsymbol{\tau} \cdot \mathbf{W}_{\mu\nu} \right\} \frac{\tilde{\varphi}}{v} u_R + \ldots$$

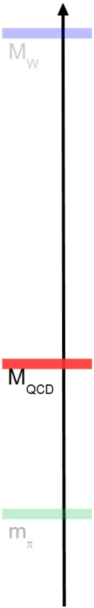
$$\mathcal{L}_{6,\,qqqq} = \Sigma_1 \left(\bar{q}^J_L u_R\right) \varepsilon_{JK} \left(\bar{q}^K_L d_R\right) + \Sigma_8 \left(\bar{q}^J_L \lambda^a u_R\right) \varepsilon_{JK} \left(\bar{q}^K_L \lambda^a d_R\right)$$

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



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

- gluon chromo-EDM (gCEDM)

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

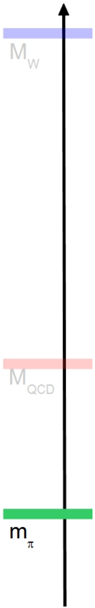
- quark EDM (qEDM) and chromo-EDM (qCEDM)

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

- TV 4-quark operators

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

Chiral properties of dimension 6 sources



1. qCEDM & qEDM

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

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

$$\tilde{W} = \frac{1}{2}\begin{pmatrix} -i\bar{q}\sigma^{\mu\nu}\gamma^5\boldsymbol{\tau}\lambda^a q \\ \bar{q}\sigma^{\mu\nu}\lambda^a q \end{pmatrix} G^a_{\mu\nu}, \qquad \tilde{V} = \frac{1}{2}\begin{pmatrix} \bar{q}\sigma^{\mu\nu}\boldsymbol{\tau}\lambda^a q \\ i\bar{q}\sigma^{\mu\nu}\gamma^5\lambda^a q \end{pmatrix} G^a_{\mu\nu}.$$

2. gCEDM & TV 4-quark operators

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

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

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**

- $M_{\not{T}} = M_W$

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

M. Pospelov and A. Ritz, '05

- 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)

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

T. Ibrahim and P. Nath, ‘08

- 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

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

The T-violating Chiral Lagrangian

Expansion in powers of $Q, m_\pi/M_{QCD}$

$$\mathcal{L}_{\not T} = \sum_{f,\,\Delta_\theta} \mathcal{L}_{\not T,f}^{(\Delta_\theta)} + \sum_{f,\Delta_6} \mathcal{L}_{\not T,f}^{(\Delta_6)}$$

- $\Delta_{\theta,6}$: count inverse powers of M_{QCD} in coefficients

$$\Delta_\theta = d + 2m + f/2 - 2 \geq 1$$

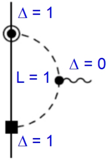
- $f = 0, 2$: # of nucleon legs
- d: # of derivatives or photon fields
- m: # of quark mass insertions

- $\Delta_6 \geq -1$

$A \leq 1$: perturbative expansion of the amplitudes

$$\mathcal{M} \sim \left(\frac{Q}{M_{QCD}}\right)^\nu$$

$$\nu = 2L + \sum_i \Delta_i, \quad M_{QCD} = 2\pi F_\pi$$



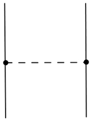
$\nu = 4$

Chiral Perturbation Theory. A $\geq$ 2

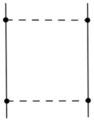
- another relevant scale:

  binding energy Q^2/m_N!

- nucleon propagator non static
- enhanced w.r.t chiral power counting



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



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

Chiral Perturbation Theory. $A \geq 2$

- another relevant scale:

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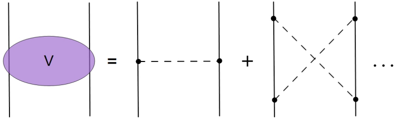
- nucleon propagator non static
- enhanced w.r.t chiral power counting

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

Weinberg:

- "irreducible diagram":
  follow χPT power counting
  define the potential V



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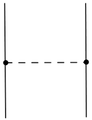

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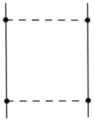

$$\sim \frac{g_A^2}{F_\pi^2}\frac{m_N Q}{4\pi F_\pi^2}$$

Weinberg:

- “irreducible diagram”:
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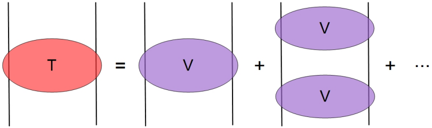
  define the potential V
- amplitude: iterate V
  Lippmann-Schwinger equation!



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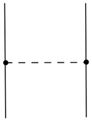
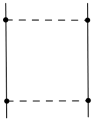


$\sim \frac{g_A^2}{F_\pi^2}$



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

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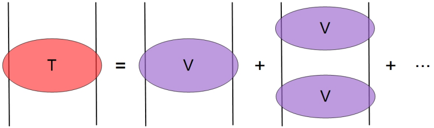

- "perturbative pions"

1. LO potential: contact S-wave operator (C_0)
2. pion exchange as perturbation: $Q/M_{NN} \ll 1$
3. $\gamma = \sqrt{m_N B}$ only relevant parameter in LO

Chiral Perturbation Theory. A $\geq$ 2

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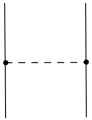

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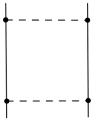

$$\sim \frac{g_A^2}{F_\pi^2} \frac{m_N Q}{4\pi F_\pi^2}$$

Weinberg:

- "irreducible diagram":
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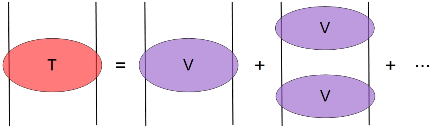


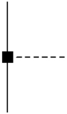
- "perturbative pions"
- "non-perturbative pions"

1. pion exchange leading effect

   $Q/M_{NN} \sim 1$

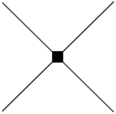
The T-violating Chiral Lagrangian: ingredients

- pion-nucleon TV interactions



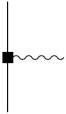
$$\mathcal{L}_{\not{T}, f=2} = -\frac{\bar{g}_0}{F_\pi}\bar{N}\boldsymbol{\pi}\cdot\boldsymbol{\tau}N - \frac{\bar{g}_1}{F_\pi}\pi_3\,\bar{N}N - \frac{\bar{g}_2}{F_\pi}\pi_3\,\bar{N}\tau_3 N$$

- 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 $\times\ F_\pi^2 Q^2$
$\bar{\theta}$ 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!

Discussion

	pion-nucleon	photon-nucleon $\times\ Q^2$	nucleon-nucleon $\times\ F_\pi^2 Q^2$
θ 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
- 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 $\times\ F_\pi^2 Q^2$
θ 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
- 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 χI	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!

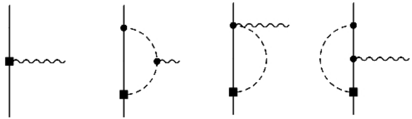
qCEDM

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

TV χI sources

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

Nucleon EDM. Theta Term



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

Leading Order

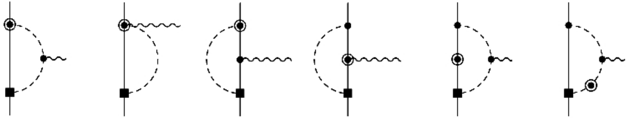
- F_0 purely determined by short-distance physics. No momentum dependence

$$d_0 = \bar{d}_0^{(3)}, \qquad S'_0 = 0,$$

- F_1 sensitive to short-distance & charged pions in the loops
  $\Longrightarrow \bar{g}_0$ only relevant π-N coupling

$$d_1 = \bar{d}_1^{(3)} + \frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2}\left[L - \ln\frac{m_\pi^2}{\mu^2}\right], \qquad S'_1 = \frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2}\,\frac{1}{6m_\pi^2},$$

R. Crewther *et al.*, '79, W. Hockings and U. Van Kolck, '05.



Next-to-Leading Order

- first non-analytic contribution & momentum dependence to $F_0(\mathbf{q}^2)$

$$d_0 = \bar{d}_0^{(3)} + \frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2}\pi\left[\frac{3m_\pi}{4m_N} - \frac{\delta m_N}{m_\pi}\right] \qquad S_0' = -\frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2}\frac{1}{6m_\pi^2}\pi\frac{\delta m_N}{2m_\pi}$$

- recoil corrections to F_1

$$d_1 = \bar{d}_1^{(3)} + \frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2}\left[L - \ln\frac{m_\pi^2}{\mu^2} + \frac{5\pi}{4}\frac{m_\pi}{m_N} - \frac{\breve{\delta} m_\pi^2}{m_\pi^2}\right],$$

$$S_1' = \frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2}\frac{1}{6m_\pi^2}\left[1 - \frac{5\pi}{4}\frac{m_\pi}{m_N} - \frac{\breve{\delta} m_\pi^2}{m_\pi^2}\right]$$

- no new T-odd LEC

Nucleon EDM. qCEDM

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

LO nucleon EDM identical to Theta Term

At NLO

- isoscalar

$$d_0 = \bar{d}_0^{(1)} + \frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2}\pi\left[\frac{3m_\pi}{4m_N}\left(1+\frac{\bar{g}_1}{3\bar{g}_0}\right) - \frac{\delta m_N}{m_\pi}\right] \qquad S_0' = -\frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2}\frac{1}{6m_\pi^2}\pi\frac{\delta m_N}{2m_\pi}$$

- isovector

$$d_1 = \bar{d}_1^{(1)} + \frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2}\left[L - \ln\frac{m_\pi^2}{\mu^2} + \frac{5\pi}{4}\frac{m_\pi}{m_N}\left(1+\frac{\bar{g}_1}{5\bar{g}_0}\right) - \frac{\breve{\delta} m_\pi^2}{m_\pi^2}\right],$$

$$S_1' = \frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2}\frac{1}{6m_\pi^2}\left[1 - \frac{5\pi}{4}\frac{m_\pi}{m_N} - \frac{\breve{\delta} m_\pi^2}{m_\pi^2}\right]$$

nucleon EDFF cannot distinguish between Theta Term and qCEDM

Nucleon EDM. Theta Term & qCEDM.

- EDM depends on π-N coupling $\bar{g}_0$, and short-distance LECs $\bar{d}_{0,1}$
- using non-analytic pieces for estimates

$$
\begin{aligned}
|d_n| = |d_0 - d_1| &\gtrsim \frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2}\left[\ln\frac{m_N^2}{m_\pi^2} + \frac{\pi}{2}\frac{m_\pi}{m_N} - \frac{\breve{\delta} m_\pi^2}{m_\pi^2} + \pi\frac{\delta m_N}{m_\pi}\right] \\
&\simeq (0.130 + 0.008 - 0.002 + 0.002)\,\frac{\bar{g}_0}{F_\pi}\, e\,\mathrm{fm}
\end{aligned}
$$

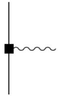
- at NLO, bound on isoscalar EDM

$$
|d_0| \gtrsim \frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2}\,\pi\left[\frac{3 m_\pi}{4 m_N} - \frac{\delta m_N}{m_\pi}\right] \simeq (0.012 - 0.002)\,\frac{\bar{g}_0}{F_\pi}\, e\,\mathrm{fm}.
$$

- $S'_{0,1}$ only depends on $\bar{g}_0$

$$
\begin{aligned}
S'_0 &= -\frac{e g_A \bar{g}_0}{12(2\pi F_\pi)^2}\frac{\pi \delta m_N}{m_\pi^2} = -0.3 \cdot 10^{-3}\,\frac{\bar{g}_0}{F_\pi}\, e\,\mathrm{fm}^3, \\
S'_1 &= \frac{e g_A \bar{g}_0}{6(2\pi F_\pi)^2}\frac{1}{m_\pi^2}\left[1 - \frac{5\pi}{4}\frac{m_\pi}{m_N} - \frac{\breve{\delta} m_\pi^2}{m_\pi^2}\right]\bar{\theta} = 4.7 \cdot 10^{-3}\,\frac{\bar{g}_0}{F_\pi}\, e\,\mathrm{fm}^3,
\end{aligned}
$$

Nucleon EDM and EDFF. qEDM & TV χI sources



- EDFF purely short-distance & momentum independent at LO

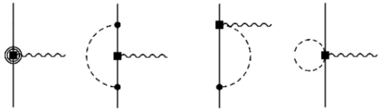
- isoscalar

$$F_0(\mathbf{q}^2) = d_0 = \bar{d}_0^{(n)}, \qquad S_0' = 0$$

- isovector

$$F_1(\mathbf{q}^2) = d_1 = \bar{d}_1^{(n)}, \quad S_1' = 0.$$

Nucleon EDM and EDFF. qEDM & TV χI 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 χI 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 χI
$M_{\rm QCD}\, d_n/e$	$\mathcal{O}\left(\bar\theta \frac{m_\pi^2}{M_{\rm QCD}^2}\right)$	$\mathcal{O}\left(\tilde\delta \frac{m_\pi^2}{M_{\not T}^2}\right)$	$\mathcal{O}\left(\delta \frac{m_\pi^2}{M_{\not T}^2}\right)$	$\mathcal{O}\left(w \frac{M_{\rm QCD}^2}{M_{\not T}^2}\right)$
d_p/d_n	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$m_\pi^2 S_1'/d_n$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{\rm QCD}^2}\right)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{\rm QCD}^2}\right)$
$m_\pi^2 S_0'/d_n$	$\mathcal{O}\left(\frac{m_\pi}{M_{\rm QCD}}\right)$	$\mathcal{O}\left(\frac{m_\pi}{M_{\rm QCD}}\right)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{\rm QCD}^2}\right)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{\rm QCD}^2}\right)$

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

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

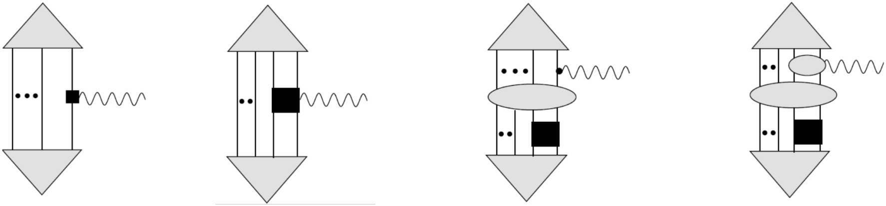
- S_1' come at the same order as d_i
- S_0' suppressed by m_π/M_{QCD} with respect to d_i
- scale for momentum variation of EDFF set by m_π

Theta Term & qCEDM

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

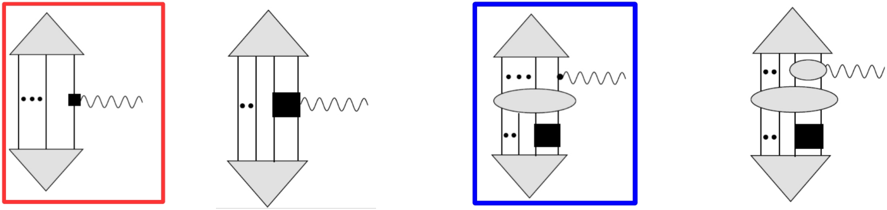
qEDM & TV χI

EDMs of Light Nuclei. Power Counting



$d_{0,1}$ $\qquad$ $\dfrac{\bar{g}_0}{m_N^2}\dfrac{Q}{M_{NN}}$ $\qquad$ $\dfrac{\bar{g}_{0,1}}{Q^2}, \bar{C}_{1,2}F_\pi^2 \times \dfrac{Q}{M_{NN}}$ $\qquad$ $\dfrac{\bar{g}_{0,1}}{m_N^2}\dfrac{Q^2}{M_{NN}^2}$

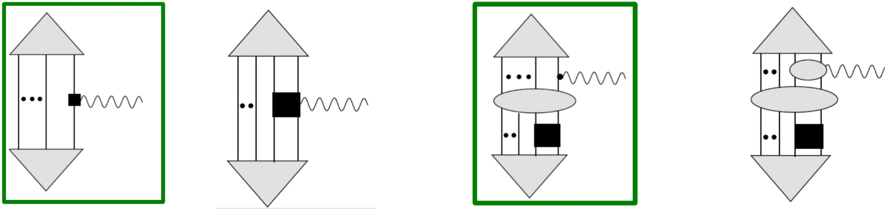
EDMs of Light Nuclei. Power Counting



$d_{0,1}$ $\qquad \frac{\bar{g}_0}{m_N^2}\frac{Q}{M_{NN}}$ $\qquad \frac{\bar{g}_{0,1}}{Q^2}, \bar{C}_{1,2}F_\pi^2 \times \frac{Q}{M_{NN}}$ $\qquad \frac{\bar{g}_{0,1}}{m_N^2}\frac{Q^2}{M_{NN}^2}$

- Theta & qCEDM: pion-exchange dominates
- qEDM: contribs. from neutron and proton EDMs dominate
- χI: one-body, pion-exchange & short range equally important.

EDMs of Light Nuclei. Power Counting



$d_{0,1}$ | $\frac{\bar{g}_0}{m_N^2}\frac{Q}{M_{NN}}$ | $\frac{\bar{g}_{0,1}}{Q^2}, \bar{C}_{1,2}F_\pi^2 \times \frac{Q}{M_{NN}}$ | $\frac{\bar{g}_{0,1}}{m_N^2}\frac{Q^2}{M_{NN}^2}$

- Theta & qCEDM: pion-exchange dominates
- qEDM: contribs. from neutron and proton EDMs dominate
- χI: one-body, pion-exchange & short range equally important.

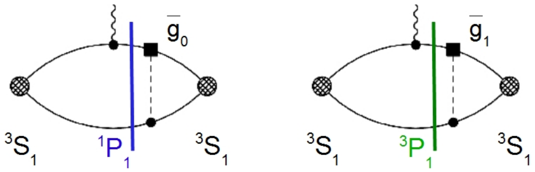
selection rules! especially for Theta Term

Deuteron EDM and MQM

Spin 1, Isospin 0 particle

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

d_d: deuteron EDM $\qquad$ $\mathcal{M}_d$: deuteron magnetic quadrupole moment (MQM).



dEDM

- isoscalar ($\bar{g}_0$, $\bar{C}_{1,2}$) TV corrections to wavefunction vanish at LO.

dMQM

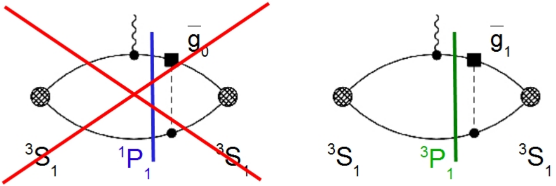
- both isoscalar & isovector corrections contribute

Deuteron EDM and MQM

Spin 1, Isospin 0 particle

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

d_d: deuteron EDM $\mathcal{M}_d$: deuteron magnetic quadrupole moment (MQM).



dEDM

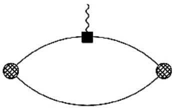
- isoscalar ($\bar{g}_0$, $\bar{C}_{1,2}$) TV corrections to wavefunction vanish at LO.

dMQM

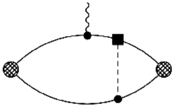
- both isoscalar & isovector corrections contribute

Deuteron EDM

One-body



TV corrections to wavefunction



- only sensitive to isoscalar nucleon EDM

$$F_D(\mathbf{q}^2) = 2d_0 \frac{4\gamma}{|\mathbf{q}|} \arctan\left(\frac{|\mathbf{q}|}{4\gamma}\right) = 2d_0 \left(1 - \frac{1}{3}\left(\frac{|\mathbf{q}|}{4\gamma}\right)^2 + \dots\right)$$

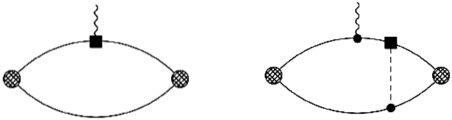
- sensitive to **isobreaking** $\bar{g}_1$

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

- relative size different for different sources!

Deuteron EDM. qCEDM

qCEDM: chiral breaking & isospin breaking



$$d_d = 2d_0 - \frac{2}{3} e \frac{g_A \bar{g}_1}{m_\pi^2} \frac{m_N m_\pi}{4\pi F_\pi^2} \frac{1+\xi}{(1+2\xi)^2} = d_n + d_p - 0.23 \frac{\bar{g}_1}{F_\pi} e\,\mathrm{fm}$$

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

deuteron EDM enhanced w.r.t. nucleon!

- $\bar{g}_1$ leading interaction
- d_0 suppressed by two powers of M_{QCD}

$$\frac{d_d}{d_n + d_p} \lesssim 10 \frac{\bar{g}_1}{\bar{g}_0}$$

using non-analytic piece of d_0

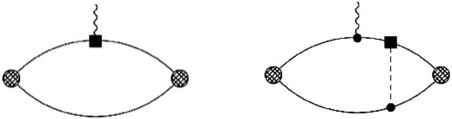
Deuteron EDM. Theta Term & TV χI Sources

Theta term: chiral breaking & isospin symmetric

TV χI Sources: chiral invariant

$\bar{g}_1$ suppressed!

D_0 enhanced!



$$d_d = 2d_0 - \frac{2}{3} e \frac{g_A \bar{g}_1}{m_\pi^2} \frac{m_N m_\pi}{4\pi F_\pi^2} \frac{1+\xi}{(1+2\xi)^2} = d_n + d_p - 0.23 \frac{\bar{g}_1}{F_\pi} e \,\text{fm}$$

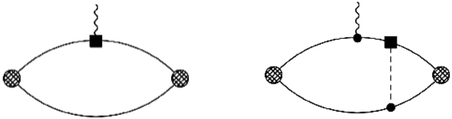
$$\mathcal{O}\left(\bar{\theta} \frac{m_\pi^2}{M_{QCD}^3}\right) \qquad \mathcal{O}\left(\bar{\theta}\varepsilon \frac{m_\pi^2}{M_{QCD}^3} \frac{m_\pi}{M_{NN}}\right)$$

- $\bar{g}_1$ & d_0 appear at the same level in the Lagrangian
- dEDM well approximated by $d_n + d_p$

Deuteron EDM. Theta Term & TV χI Sources

Theta term: chiral breaking & isospin symmetric
TV χI Sources: chiral invariant

$\bar{g}_1$ suppressed!
D_0 enhanced!



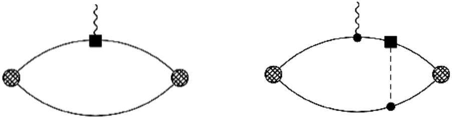
$$d_d = 2d_0 - \frac{2}{3} e \frac{g_A \bar{g}_1}{m_\pi^2} \frac{m_N m_\pi}{4\pi F_\pi^2} \frac{1+\xi}{(1+2\xi)^2} = d_n + d_p - 0.23 \frac{\bar{g}_1}{F_\pi} e \, \mathrm{fm}$$

$$\approx 0.02 \frac{\bar{g}_0}{F_\pi} e \, \mathrm{fm} \qquad \approx 0.23 \times 0.01 \frac{\bar{g}_0}{F_\pi} e \, \mathrm{fm}$$

- $\bar{g}_1$ & 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 $\alpha_{\rm em}$



$$d_d = 2d_0 - \frac{2}{3} e \frac{g_A \bar{g}_1}{m_\pi^2} \frac{m_N m_\pi}{4\pi F_\pi^2} \frac{1+\xi}{(1+2\xi)^2} = d_n + d_p - 0.23 \frac{\bar{g}_1}{F_\pi} \, e\,\mathrm{fm}$$

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

- dEDM well approximated by $d_n + d_p$

Deuteron EDM. Non perturbative results

"Hybrid approach"

- realistic potentials for TC interactions (AV18, Reid93, Nijmegen II)
- EFT potential for TV interactions

ok...
if observable not too sensitive to short distance details

$$d_d = d_n + d_p - 0.19\,\frac{\bar{g}_1}{F_\pi}\,e\,\mathrm{fm}\ ,$$

for AV18,
different potentials agree at $\sim 5\%$

- in good agreement with perturbative calculation!

1. $\bar{g}_1$ contrib. agrees at $\sim 20\%$
2. for theta, formally LO pion-exchange terms are small

Deuteron EDM. Non perturbative results

"Hybrid approach"

- realistic potentials for TC interactions (AV18, Reid93, Nijmegen II)
- EFT potential for TV interactions

ok...
if observable not too sensitive to short distance details

$$d_d(\bar{\theta}) = d_n + d_p + \left[-0.19\,\frac{\bar{g}_1}{F_\pi} + \left(0.2 - 0.7 \cdot 10^2\,\beta_1\right) \cdot 10^{-3}\,\frac{\bar{g}_0}{F_\pi}\right]\, e\,\mathrm{fm}\,,$$

for AV18,
different potentials agree at $\sim 5\%$

- in good agreement with perturbative calculation!

1. $\bar{g}_1$ contrib. agrees at $\sim 20\%$
2. for theta, formally LO pion-exchange terms are small

Deuteron EDM. Summary

Source	$\bar{\theta}$	qCEDM	qEDM	TV χI
$M_{QCD}\, d_d/e$	$\mathcal{O}\left(\bar{\theta}\,\frac{m_\pi^2}{M_{QCD}^2}\right)$	$\mathcal{O}\left(\tilde{\delta}\,\frac{m_\pi M_{QCD}^2}{M_{NN} M_{\not{T}}^2}\right)$	$\mathcal{O}\left(\delta\,\frac{m_\pi^2}{M_{\not{T}}^2}\right)$	$\mathcal{O}\left(w\,\frac{M_{QCD}^2}{M_{\not{T}}^2}\right)$
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 χI sources
- only for qCEDM, $d_d \gg d_n + d_p$

qCEDM

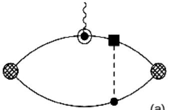
- deuteron EDM experiment more sensitive than neutron & proton EDM

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

- nucleon and deuteron EDM *qualitatively* pinpoint qCEDM.

Deuteron MQM. Chiral Breaking Sources

Corrections to wavefunction



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

qCEDM

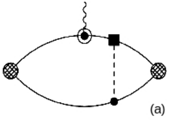
- $\bar{g}_0$ and $\bar{g}_1$ equally important
- dEDM and dMQM comparable

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

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

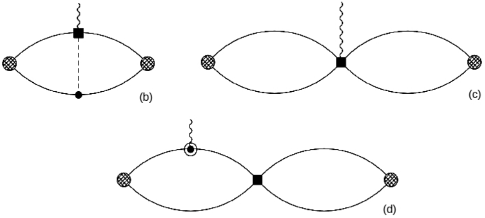
- only $\bar{g}_0$ contributes
- dMQM bigger than dEDM

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

using non-analytic piece of d_0.

Deuteron MQM. qEDM & TV χI 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

EDM of ^{3}He and ^{3}H

- AV18, EFT potentials for TC interactions

code of I. Stetcu *et al.*, '08

- agreement at the level of 15% for one-body & long-range contribs.
- no agreement for short range contribution ($\bar{C}_{1,2}$)

$$d_{^3\mathrm{He}} = 0.88\, d_n - 0.047\, d_p - \left(0.15\, \frac{\bar{g}_0}{F_\pi} + 0.28\, \frac{\bar{g}_1}{F_\pi} + 0.01\, F_\pi^3\, \bar{C}_1 - 0.02\, F_\pi^3\, \bar{C}_2\right) e\,\mathrm{fm}$$

and

$$d_{^3\mathrm{H}} = -0.050\, d_n + 0.90\, d_p + \left(0.15\, \frac{\bar{g}_0}{F_\pi} - 0.28\, \frac{\bar{g}_1}{F_\pi} + 0.01\, F_\pi^3\, \bar{C}_1 - 0.02\, F_\pi^3\, \bar{C}_2\right) e\,\mathrm{fm}\,,$$

for AV18

- for EFT, $\bar{C}_{1,2}$ contribs. five time bigger
- need fully consistent calculation for χI sources...

... maybe...

EDM of ^{3}He and ^{3}H. qCEDM

$$
\begin{aligned}
d_{^3\mathrm{He}}(\mathrm{qCEDM}) &= 0.83\, d_0 - 0.93\, d_1 - \left(0.15\, \frac{\bar{g}_0}{F_\pi} + 0.28\, \frac{\bar{g}_1}{F_\pi}\right) e\,\mathrm{fm}\,, \\
d_{^3\mathrm{H}}(\mathrm{qCEDM}) &= 0.85\, d_0 + 0.95\, d_1 + \left(0.15\, \frac{\bar{g}_0}{F_\pi} - 0.28\, \frac{\bar{g}_1}{F_\pi}\right) e\,\mathrm{fm}\,. \\
&\sim 0.1\, \frac{\bar{g}_0}{F_\pi}\, e\,\mathrm{fm}
\end{aligned}
$$

- one-body pieces more important than expected by naive power counting
- *qualitatively*:
  ^{3}He and ^{3}H EDMs significantly different from neutron and proton EDMs
- *quantitatively*: if nucleon & deuteron observed

1. $d_{^3\mathrm{He}} + d_{^3\mathrm{H}}$ testable prediction of the theory

$$
d_{^3\mathrm{He}} + d_{^3\mathrm{H}} = 1.68 d_0 + 0.02 d_1 - 0.56\, \frac{\bar{g}_1}{F_\pi}\, e\,\mathrm{fm}
$$

2. use $d_{^3\mathrm{He}} - d_{^3\mathrm{H}}$ to extract $\bar{g}_0$ & predict other TV observable

deuteron MQM, proton Schiff moment

EDM of ^{3}He and ^{3}H. Theta term

$$
\begin{aligned}
d_{^3\mathrm{He}}(\bar\theta) &= 0.83\, d_0 - 0.93\, d_1 - 0.15\, \frac{\bar g_0}{F_\pi}\, e\,\mathrm{fm}\,, \\
d_{^3\mathrm{H}}(\bar\theta) &= 0.85\, d_0 + 0.95\, d_1 + 0.15\, \frac{\bar g_0}{F_\pi}\, e\,\mathrm{fm}\,.
\end{aligned}
$$

- one-body piece more important than naive power counting

- $d_{^3\mathrm{He}} + d_{^3\mathrm{H}}$ well approximated by $d_n + d_p$
- $d_{^3\mathrm{He}} - d_{^3\mathrm{H}}$ significantly different from $2d_1$

$$
d_{^3\mathrm{He}} - d_{^3\mathrm{H}} = -0.02 d_0 - 1.88 d_1 - 0.30 \frac{\bar g_0}{F_\pi}\, e\,\mathrm{fm}
$$

- one more observable for quantitative prediction

deuteron MQM, proton Schiff moment

EDM of ^{3}He and ^{3}H. qEDM & χI sources

$$
\begin{aligned}
d_{^3\mathrm{He}}(\mathrm{qEDM}) &= 0.83\, d_0 - 0.93\, d_1 \ , \\
d_{^3\mathrm{H}}(\mathrm{qEDM}) &= 0.85\, d_0 + 0.95\, d_1 \ .
\end{aligned}
$$

- no deviation from d_n, d_p

$$
\begin{aligned}
d_{^3\mathrm{He}}(\chi\mathrm{I}) &= 0.83\, d_0 - 0.93\, d_1 - \left(0.15\, \frac{\bar{g}_0}{F_\pi} + 0.28\, \frac{\bar{g}_1}{F_\pi} + 0.01\, F_\pi^3 \bar{C}_1 - 0.02\, F_\pi^3 \bar{C}_2\right) e\,\mathrm{fm} \ , \\
d_{^3\mathrm{H}}(\chi\mathrm{I}) &= 0.85\, d_0 + 0.95\, d_1 + \left(0.15\, \frac{\bar{g}_0}{F_\pi} - 0.28\, \frac{\bar{g}_1}{F_\pi} + 0.01\, F_\pi^3 \bar{C}_1 - 0.02\, F_\pi^3 \bar{C}_2\right) e\,\mathrm{fm} \ . \\
&\sim 1.9\, \frac{\bar{g}_0}{F_\pi}\, e\,\mathrm{fm} \qquad \text{naive dim. analysis}
\end{aligned}
$$

- formally, all of the same size
- numerically, one-body contribution dominates

hard to differentiate between qEDM and χI sources!

Summary & Conclusion

EFT approach

1. consistent framework to treat one, two and three nucleon TV observables
2. qualitative relations between one, two and three nucleon observables, specific to TV source
3. particularly promising for qCEDM and Theta Term

identify/exclude them in next generation of experiments?

4. not much hope to distinguish between qEDM and χI sources

other observables? TV observables w/o photons?

To-do list

1. beyond NDA
2. improve calculation
3. other observables, deuteron MQM, proton Schiff moment

- compute LECs on the lattice
- NLO with perturbative pions
- fully consistent non ptb. calculation
- study atomic EDMs?

Backup Slides

Electromagnetic and T-violating 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 T-violating operators

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

- S_4

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

- $S_4 \otimes T_{34}$

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

- same chiral properties as partners of $\not{T}$ 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 $\not{T}$ 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

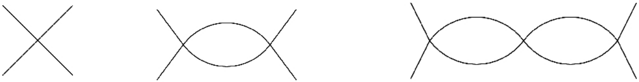
T-even sector

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

- 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 $\quad$ $C_0 \frac{m_N Q}{4\pi} C_0$ $\quad$ $C_0 \left(\frac{m_N Q}{4\pi} C_0\right)^2$

Deuteron EDM and MQM. KSW Power Counting

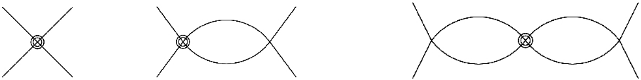
T-even sector

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

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

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

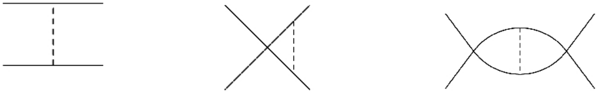
- iterate C_0 at all orders
- operators which connect S-waves get enhanced $C_2^{^3S_1} = \mathcal{O}\left(\frac{4\pi}{m_N\Lambda_{NN}}\frac{1}{\mu^2}\right)$



$C_0\frac{Q}{\Lambda_{NN}}$ $\quad$ $C_0\frac{Q}{\Lambda_{NN}}\ \frac{m_N Q}{4\pi}C_0$ $\quad$ $C_0\frac{Q}{\Lambda_{NN}}\ \left(\frac{m_N Q}{4\pi}C_0\right)^2$

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

Perturbative pion approach:

- expansion in Q/Λ_{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

- treat pion exchange as a perturbation

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

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

Perturbative pion approach:

- expansion in Q/Λ_{NN}, with $Q \in \{|\mathbf{q}|, m_\pi, \gamma = \sqrt{m_N B}\}$
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Deuteron EDM and MQM. KSW Power Counting

$\not{T}$-odd sector

a. four-nucleon $\not{T}$-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
$C_{i,\not{T}}$	$\frac{4\pi}{\mu m_N} \bar{\theta} \frac{m_\pi^2}{M_{QCD} \Lambda_{NN}^2}$	$\frac{4\pi}{\mu m_N} \tilde{\delta} \frac{m_\pi^2}{M_{\not{T}}^2 M_{QCD}}$	0	$\frac{4\pi}{\mu m_N} \frac{w}{M_{\not{T}}^2} \Lambda_{NN}$

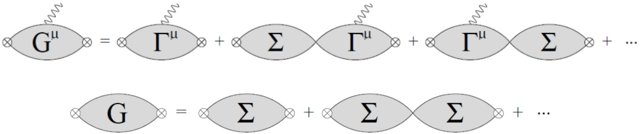
b. four-nucleon $\not{T}$-odd currents

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

- in the PDS scheme

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

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

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