EDMs of Light Nuclei in Chiral Effective Theory

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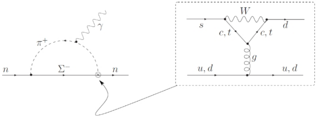
BERKELEY LAB Lawrence Berkeley National Laboratory

Motivations

Electric Dipole Moments (EDMs) are ideal place to look for new physics

- signal of T and P violation
- signal T violation in the flavor diagonal sector
- 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

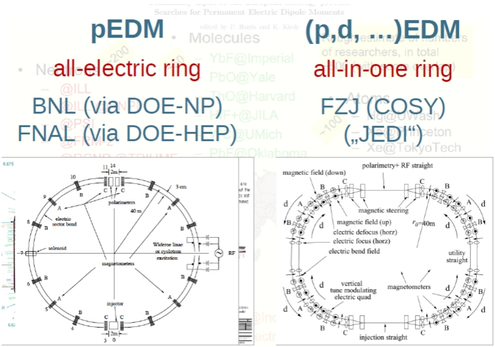
  ^{199}Hg EDM @ Univ. of Washington

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

Large window for new physics and intense experimental activity!

Motivations

- EDM of charged particles in storage ring experiments



from H. Ströher, talk at "EDM Searches at Storage Rings". ECT*, Trento, '12.

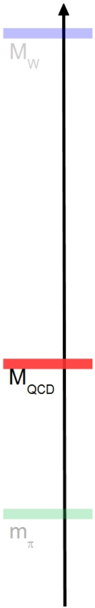
- accuracy goal: $d_{p,\,d,\,\mathrm{He}} \sim 10^{-16}\ e$ fm.

Motivations

Why EDMs of light nuclei?

- complementary to nucleon EDM
  - sensitive to different low-energy $\not{P}\not{T}$ couplings $(\bar{g}_0, \bar{g}_1, \bar{d}_1, \ldots)$
  - clues on properties of $\not{P}\not{T}$ sources at high energy $SU(2)$, isospin
  - can tell QCD $\bar{\theta}$ term apart from new physics?
- χPT and Nuclear EFT
  - Tools for precise and controlled calculations (in terms of EFT couplings)
- combination of EFT & lattice QCD
  - first principle calculation of d_n, d_d and d_{He}, for $\bar{\theta}$ and dimension-six operators

The QCD $\bar{\theta}$ term.

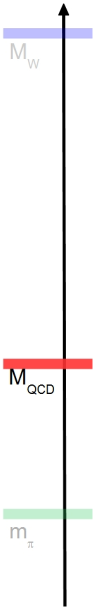


Dimension 4

$$
\begin{aligned}
\mathcal{L}_4 &= -\theta \frac{g_s^2}{64\pi^2} \varepsilon^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta} - e^{i\rho} \bar{q}_R M q_L - e^{-i\rho} \bar{q}_L M q_R, \\
M &= \bar{m} \begin{pmatrix} 1-\varepsilon & 0 \\ 0 & 1+\varepsilon \end{pmatrix} \qquad \begin{array}{r} \bar{m} = (m_u + m_d)/2 \\ \varepsilon = (m_d - m_u)/(m_d + m_u) \end{array}
\end{aligned}
$$

$\bar{\theta}$ term intimately related to the quark masses

- unphysical if $m_{u,d} = 0$



Dimension 4

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

$$m_* = \frac{m_u m_d}{m_d + m_d}, \qquad r(\bar{\theta}) = \sqrt{\frac{1+\varepsilon^2 \tan^2\frac{\bar{\theta}}{2}}{1+\tan^2\frac{\bar{\theta}}{2}}}$$

$\bar{\theta}$ term intimately related to the quark masses

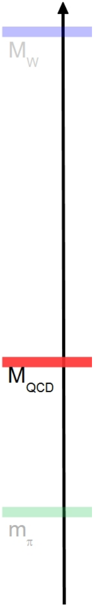
- unphysical if $m_{u,d} = 0$

After anomalous $U_A(1)$ rotation & vacuum alignment

- explicitly break chiral symmetry, conserves isospin
- related to the quark mass difference by an axial $SU_A(2)$ rotation.

$$\bar{q}i\gamma_5 q \xrightarrow{SU_2(A)} \bar{q}\tau_3 q$$

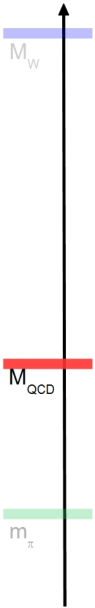
Dimension-six operators. Quark-gluon Lagrangian.



Dimension 6

$$
\begin{aligned}
\mathcal{L}_6 \quad = \quad & -\frac{1}{2}\bar{q}\left(d_0 + d_3\tau_3\right) i\sigma^{\mu\nu}\gamma_5 q\, F_{\mu\nu} - \frac{1}{2}\bar{q}\left(\tilde{d}_0 + \tilde{d}_3\tau_3\right) i\sigma^{\mu\nu}\gamma_5\lambda^a q\, G^a_{\mu\nu} \\
& + \frac{d_W}{6} f^{abc}\epsilon^{\mu\nu\alpha\beta} G^a_{\alpha\beta} G^b_{\mu\rho} G^{c\ \rho}_{\nu} \\
& + \frac{\mathrm{Im}\,\Xi_{(1,8)}}{4}\epsilon^{3ij}\bar{q}\tau^i\gamma^\mu q\,\bar{q}\tau^j\gamma_\mu\gamma_5 q + \frac{\mathrm{Im}\Sigma_{(1,8)}}{4}\left(\bar{q}q\,\bar{q}i\gamma_5 q - \bar{q}\boldsymbol{\tau}q\ \cdot \bar{q}\boldsymbol{\tau}i\gamma_5 q\right)
\end{aligned}
$$

Dimension-six operators. Quark-gluon Lagrangian.



Dimension 6

$$\mathcal{L}_6 = -\frac{1}{2}\bar{q}\,(d_0 + d_3\tau_3)\,i\sigma^{\mu\nu}\gamma_5 q\,F_{\mu\nu} - \frac{1}{2}\bar{q}\left(\tilde{d}_0 + \tilde{d}_3\tau_3\right)i\sigma^{\mu\nu}\gamma_5\lambda^a q\,G^a_{\mu\nu}$$
$$+\frac{d_W}{6} f^{abc}\epsilon^{\mu\nu\alpha\beta}G^a_{\alpha\beta}G^b_{\mu\rho}G^{c\,\rho}_{\nu}$$
$$+\frac{\mathrm{Im}\,\Xi_{(1,8)}}{4}\epsilon^{3ij}\bar{q}\tau^i\gamma^\mu q\,\bar{q}\tau^j\gamma_\mu\gamma_5 q + \frac{\mathrm{Im}\Sigma_{(1,8)}}{4}\left(\bar{q}q\,\bar{q}i\gamma_5 q - \bar{q}\boldsymbol{\tau}q\cdot\bar{q}\boldsymbol{\tau}i\gamma_5 q\right)$$

qEDM and qCEDM

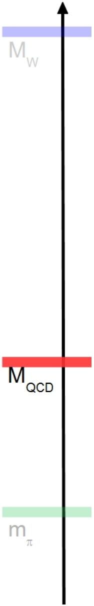
- break $SU_L(2)$ (need insertion of Higgs VEV)
- break isospin
- related by axial rotation to the quark (chromo-) magnetic moments.

$$\bar{q}i\sigma^{\mu\nu}\gamma_5 G_{\mu\nu}q \xrightarrow{SU_2(A)} \bar{q}\tau_3\sigma^{\mu\nu}G_{\mu\nu}q$$
$$\bar{q}i\sigma^{\mu\nu}\gamma_5\tau_3 G_{\mu\nu}q \xrightarrow{SU_2(A)} \bar{q}\sigma^{\mu\nu}G_{\mu\nu}q$$

Weinberg three-gluon operator

- chiral invariant

Dimension-six operators. Quark-gluon Lagrangian.



Dimension 6

$$
\begin{aligned}
\mathcal{L}_6 \;=\;& -\frac{1}{2}\bar{q}\,(d_0 + d_3\tau_3)\, i\sigma^{\mu\nu}\gamma_5 q\, F_{\mu\nu} - \frac{1}{2}\bar{q}\left(\tilde{d}_0 + \tilde{d}_3\tau_3\right) i\sigma^{\mu\nu}\gamma_5\lambda^a q\, G^a_{\mu\nu} \\
& + \frac{d_W}{6} f^{abc}\epsilon^{\mu\nu\alpha\beta} G^a_{\alpha\beta} G^b_{\mu\rho} G^{c\,\rho}_{\nu} \\
& + \frac{\mathrm{Im}\,\Xi_{(1,8)}}{4}\epsilon^{3ij}\bar{q}\tau^i\gamma^\mu q\,\bar{q}\tau^j\gamma_\mu\gamma_5 q + \frac{\mathrm{Im}\Sigma_{(1,8)}}{4}\left(\bar{q}q\,\bar{q}i\gamma_5 q - \bar{q}\boldsymbol{\tau}q\cdot\bar{q}\boldsymbol{\tau}i\gamma_5 q\right)
\end{aligned}
$$

Four-quark operators

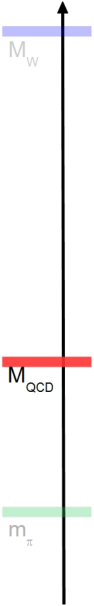
- only four four-quark operators are genuine dimension-six
- other combinations suppressed by $\bar{m}/M_W$

- $\Sigma_{1,8}$ do not break chiral symmetry/isospin
- $\Xi_{1,8}$ break $SU_L(2)$& isospin
  generated when integrate out $W^{\pm}$.

J. Ng and S. Tulin, ‘11.

- $\Xi_{1,8}$ break $SU_L(2)$& isospin differently from qCEDM
  tensor vs. vector under $SU_L(2)\times SU_R(2)$

Dimension-six operators. Quark-gluon Lagrangian.



Dimension 6

$$
\begin{aligned}
\mathcal{L}_6 \;=\;& -\frac{1}{2}\bar q\,(d_0 + d_3\tau_3)\, i\sigma^{\mu\nu}\gamma_5 q\, F_{\mu\nu} - \frac{1}{2}\bar q\left(\tilde d_0 + \tilde d_3\tau_3\right) i\sigma^{\mu\nu}\gamma_5\lambda^a q\, G^a_{\mu\nu} \\
&+\frac{d_W}{6} f^{abc}\epsilon^{\mu\nu\alpha\beta} G^a_{\alpha\beta} G^b_{\mu\rho} G^{c\,\rho}_{\nu} \\
&+\frac{\mathrm{Im}\,\Xi_{(1,8)}}{4}\epsilon^{3ij}\bar q\tau^i\gamma^\mu q\,\bar q\tau^j\gamma_\mu\gamma_5 q + \frac{\mathrm{Im}\Sigma_{(1,8)}}{4}\left(\bar q q\,\bar q i\gamma_5 q - \bar q\boldsymbol{\tau} q\,\cdot\bar q\boldsymbol{\tau} i\gamma_5 q\right)
\end{aligned}
$$

- Coefficients (at $\mu \sim 1$ GeV)

$$
d_W \equiv 4\pi\frac{w}{M_{\not T}^2}, \qquad d_{0,3}\equiv e\delta_{0,3}\frac{\bar m}{M_{\not T}^2}, \qquad \tilde d_{0,3}\equiv 4\pi\tilde\delta_{0,3}\frac{\bar m}{M_{\not T}^2},
$$

$$
\mathrm{Im}\,\Sigma_{1,8} \equiv (4\pi)^2\frac{\sigma_{1,8}}{M_{\not T}^2}, \qquad \mathrm{Im}\,\Xi_{1,8}\equiv(4\pi)^2\frac{\xi_{1,8}}{M_{\not T}^2}.
$$

- depend on details of BSM TV mechanism
- contain info on QCD running & heavy SM particles

Chiral Perturbation Theory.

- pion couples weakly at scales $Q \ll M_{QCD} \sim 2\pi F_\pi$
- $\mathcal{L}_{\text{EFT}}$ contains all operators allowed by QCD symmetries
- $\mathcal{L}_{\text{EFT}}$ organized as expansion in powers of $Q, m_\pi / M_{QCD}$

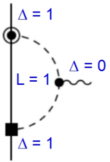
$$\mathcal{L}_{\text{EFT}}[\boldsymbol{\pi}, N] = \sum_{f,\,\Delta} \mathcal{L}_f^{(\Delta)}[\boldsymbol{\pi}, N]$$

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

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

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

$$\begin{aligned} \mathcal{T} &\sim \left(\frac{Q}{M_{QCD}}\right)^{\nu} \\ \nu &= 2L + \sum_i \Delta_i, \quad M_{QCD} = 2\pi F_\pi \end{aligned}$$



$\nu = 4$

Effective Lagrangian for $\not{P}\not{T}$ interactions.

$$\mathcal{L}_{\not{P}\not{T}} = \mathcal{L}_{\pi} + \mathcal{L}_{\pi N} + \mathcal{L}_{\gamma N} + \mathcal{L}_{NN} + \dots$$

- remove pion tadpoles order by order in χPT (vacuum alignment)
- at least 3π interactions, usually suppressed for EDMs

$$\mathcal{L}_{\pi} = -\bar{\Delta}\, \pi_3 \frac{\pi^2}{F_\pi} + \dots$$

- non-derivative pion-nucleon couplings

$$\mathcal{L}_{\pi N} = -\frac{\bar{g}_0}{F_\pi} \bar{N} \boldsymbol{\pi} \cdot \boldsymbol{\tau} N - \frac{\bar{g}_1}{F_\pi} \pi_3\, \bar{N} N + \dots$$

- short-range EDM operators

$$\mathcal{L}_{\gamma N} \quad = \quad -2\bar{N} S^\mu v^\nu \left(\bar{d}_0 + \bar{d}_1 \tau_3\right) N\, F_{\mu\nu} + \dots$$

- nucleon-nucleon interactions

$$\mathcal{L}_{NN} \quad = \quad \bar{C}_1 \bar{N} S^\mu N\, \partial_\mu \left(\bar{N} N\right) + \bar{C}_2 \bar{N} S^\mu \boldsymbol{\tau} N \cdot \partial_\mu \left(\bar{N} \boldsymbol{\tau} N\right) + \dots$$

TV Chiral Lagrangian. Theta Term

	$\bar{g}_0$	$\bar{g}_1$	$\bar{d}_{0,1} \times Q^2$	$\bar{C}_{1,2} \times F_\pi^2 Q^2$	
$\bar{\theta} \times \frac{m_\pi^2}{M_{QCD}}$	1	$\varepsilon \frac{m_\pi^2}{M_{QCD}^2}$	$\frac{Q^2}{M_{QCD}^2}$	$\frac{Q^2}{M_{QCD}^2}$	NDA

Theta Term violates chiral symmetry & conserves isospin

- non-derivative coupling $\bar{g}_0$ appears @ LO
- needs extra insertion of $\bar{m}\varepsilon$ to generate $\bar{g}_1$
- higher dimensionality of $N\gamma$ and NN operators costs powers of Q/M_{QCD}

TV Chiral Lagrangian. Theta Term

	$\bar{g}_0$	$\bar{g}_1$	$\bar{d}_{0,1} \times Q^2$	$\bar{C}_{1,2} \times F_\pi^2 Q^2$	
$\bar{\theta} \times \frac{m_\pi^2}{M_{QCD}}$	1	0.01	$\frac{Q^2}{M_{QCD}^2}$	$\frac{Q^2}{M_{QCD}^2}$	NDA
$\bar{\theta} \times \frac{m_\pi^2}{M_{QCD}}$	0.11	~ 0.03			isospin

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Beyond NDA? $\bar{q}i\gamma_5 q \xrightarrow{SU_A(2)} \bar{q}\tau_3 q$

- $\bar{g}_0$ related to the hadronic contribution to $m_n - m_p$, δm_N

$$\bar{g}_0 = \delta m_N \frac{1-\varepsilon^2}{2\varepsilon}\bar{\theta}, \qquad \frac{\delta m_N}{2\varepsilon} = 2.8 \pm 0.7 \pm 0.6\,\mathrm{MeV}$$

R. Crewther *et al*, '79; S. Beane *et al*, '07

somewhat smaller than NDA.

- better lattice estimate of δm_N coming soon. A. Walker-Loud *et al*, *in preparation*

TV Chiral Lagrangian. Theta Term

	$\bar{g}_0$	$\bar{g}_1$	$\bar{d}_{0,1} \times Q^2$	$\bar{C}_{1,2} \times F_\pi^2 Q^2$	
$\bar{\theta} \times \frac{m_\pi^2}{M_{QCD}}$	1	0.01	$\frac{Q^2}{M_{QCD}^2}$	$\frac{Q^2}{M_{QCD}^2}$	NDA
$\bar{\theta} \times \frac{m_\pi^2}{M_{QCD}}$	0.11	~ 0.03			isospin

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- higher dimensionality of $N\gamma$ and NN operators costs powers of Q/M_{QCD}

Beyond NDA? $$\bar{q}i\gamma_5 q \xrightarrow{SU_A(2)} \bar{q}\tau_3 q$$

- $\bar{g}_1$ *in principle* fixed by isospin breaking observables
  in practice estimated w. assumptions,
  e.g. resonance saturation Lebedev *et al*, '04; J. Bsaisou, *et al.*, '12.
- no constraints on $\bar{d}_{0,1}$

TV Chiral Lagrangian. qCEDM & $\Xi_{1,8}$

	$\bar{g}_0$	$\bar{g}_1$	$\bar{\Delta}/Q$	$\bar{d}_{0,1} \times Q^2$	$\bar{C}_{1,2} \times F_\pi^2 Q^2$
$\tilde{\delta}_0 \times \frac{m_\pi^2 M_{QCD}}{M_{\not T}^2}$	1	$\varepsilon \frac{m_\pi^2}{M_{QCD}^2}$	$\frac{Q}{M_{QCD}}$	$\frac{Q^2}{M_{QCD}^2}$	$\frac{Q^2}{M_{QCD}^2}$
$\tilde{\delta}_3 \times \frac{m_\pi^2 M_{QCD}}{M_{\not T}^2}$	ε	1	$\frac{Q}{M_{QCD}}$	$\frac{Q^2}{M_{QCD}^2}$	$\varepsilon \frac{Q^2}{M_{QCD}^2}$
$(\xi_1, \xi_8) \times \frac{M_{QCD}^3}{M_{\not T}^2}$	ε	1	$\frac{M_{QCD}}{Q}$	$\frac{Q^2}{M_{QCD}^2}$	$\varepsilon \frac{Q^2}{M_{QCD}^2}$

- $\tilde{\delta}_0$ generates same operators as $\bar{\theta}$

TV Chiral Lagrangian. qCEDM & $\Xi_{1,8}$

	$\bar{g}_0$	$\bar{g}_1$	$\bar{\Delta}/Q$	$\bar{d}_{0,1} \times Q^2$	$\bar{C}_{1,2} \times F_\pi^2 Q^2$
$\tilde{\delta}_0 \times \frac{m_\pi^2 M_{QCD}}{M_{\not{T}}^2}$	1	$\varepsilon \frac{m_\pi^2}{M_{QCD}^2}$	$\frac{Q}{M_{QCD}}$	$\frac{Q^2}{M_{QCD}^2}$	$\frac{Q^2}{M_{QCD}^2}$
$\tilde{\delta}_3 \times \frac{m_\pi^2 M_{QCD}}{M_{\not{T}}^2}$	ε	1	$\frac{Q}{M_{QCD}}$	$\frac{Q^2}{M_{QCD}^2}$	$\varepsilon \frac{Q^2}{M_{QCD}^2}$
$(\xi_1, \xi_8) \times \frac{M_{QCD}^3}{M_{\not{T}}^2}$	ε	1	$\frac{M_{QCD}}{Q}$	$\frac{Q^2}{M_{QCD}^2}$	$\varepsilon \frac{Q^2}{M_{QCD}^2}$

- $\tilde{\delta}_0$ generates same operators as $\bar{\theta}$

Isospin-breaking sources $\tilde{\delta}_3$ and $\xi_{1,8}$

- very similar couplings
- $\bar{g}_1$ already in LO
- contribute to isoscalar couplings via vacuum alignment

TV Chiral Lagrangian. qCEDM & $\Xi_{1,8}$

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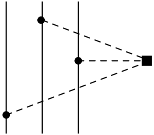
$\tilde{\delta}_3 \times \frac{m_\pi^2 M_{QCD}}{M_{\not{T}}^2}$	ε	1	$\frac{Q}{M_{QCD}}$	$\frac{Q^2}{M_{QCD}^2}$	$\varepsilon \frac{Q^2}{M_{QCD}^2}$
$(\xi_1, \xi_8) \times \frac{M_{QCD}^3}{M_{\not{T}}^2}$	ε	1	$\frac{M_{QCD}}{Q}$	$\frac{Q^2}{M_{QCD}^2}$	$\varepsilon \frac{Q^2}{M_{QCD}^2}$

- $\tilde{\delta}_0$ generates same operators as $\bar{\theta}$

Isospin-breaking sources $\tilde{\delta}_3$ and $\xi_{1,8}$

- very similar couplings
- $\bar{g}_1$ already in LO
- contribute to isoscalar couplings via vacuum alignment

- for $\xi_{1,8}$ 3π coupling is important
- generates LO three-body force



TV Chiral Lagrangian. qCEDM & $\Xi_{1,8}$

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$\tilde{\delta}_0 \times \frac{m_\pi^2 M_{QCD}}{M_{\not{T}}^2}$	1	$\varepsilon \frac{m_\pi^2}{M_{QCD}^2}$	$\frac{Q}{M_{QCD}}$	$\frac{Q^2}{M_{QCD}^2}$	$\frac{Q^2}{M_{QCD}^2}$
$\tilde{\delta}_3 \times \frac{m_\pi^2 M_{QCD}}{M_{\not{T}}^2}$	ε	1	$\frac{Q}{M_{QCD}}$	$\frac{Q^2}{M_{QCD}^2}$	$\varepsilon \frac{Q^2}{M_{QCD}^2}$
$(\xi_1, \xi_8) \times \frac{M_{QCD}^3}{M_{\not{T}}^2}$	ε	1	$\frac{M_{QCD}}{Q}$	$\frac{Q^2}{M_{QCD}^2}$	$\varepsilon \frac{Q^2}{M_{QCD}^2}$

Beyond NDA? $\quad \bar{q} i\sigma^{\mu\nu}\gamma^5(\tau_3)q \xrightarrow{SU_A(2)} \bar{q}\sigma^{\mu\nu}\tau_3(1)q$

- $\bar{g}_0$ and $\bar{g}_1$ related to corrections to m_π, m_N and δm_N from qCMDM e.g.

$$\bar{g}_1 = -2\left(\Delta_6 m_N - \Delta m_N \frac{\Delta_6 m_\pi^2}{m_\pi^2}\right)\frac{\tilde{d}_3}{\tilde{c}_0}$$

- $\Delta_6 m_\pi^2$, $\Delta_6 m_N$ and $\delta_6 m_N$ accessible on the lattice? (w/o CP violation)
- no chiral symmetry constraint on $\bar{d}_{0,1}$

TV Chiral Lagrangian. gCEDM, $\Sigma_{1,8}$ & qEDM

	$\bar{g}_0$	$\bar{g}_1$	$\bar{d}_{0,1} \times Q^2$	$\bar{C}_{1,2} \times F_\pi^2 Q^2$
$(w, \sigma_1, \sigma_8) \times \frac{M_{QCD}}{M_{\not T}^2}$	m_π^2	$m_\pi^2 \varepsilon$	Q^2	Q^2
$\delta_{0,3} \times \frac{m_\pi^2 M_{QCD}}{M_{\not T}^2}$	$\frac{\alpha_{\rm em}}{4\pi}$	$\frac{\alpha_{\rm em}}{4\pi}$	$\frac{Q^2}{M_{QCD}^2}$	$\frac{\alpha_{\rm em}}{4\pi} \frac{Q^2}{M_{QCD}^2}$

gCEDM, $\Sigma_{1,8}$ respect chiral symmetry (χISs)

- $\bar{g}_{0,1}$ generated through insertion of the quark mass and mass difference

  extra m_π^2/M_{QCD}^2 suppression!

- NN and $N\gamma$ couplings do not break chiral symmetry

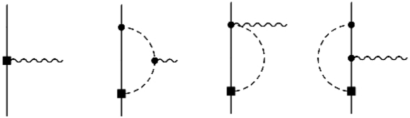
  no extra suppression

- same importance for long & short range operators

qEDM

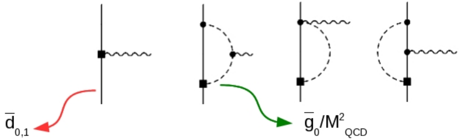
- hadronic operators suppressed by $\alpha_{\rm em}$
- only $\bar{d}_{0,1}$ relevant

Nucleon EDM. $\bar{\theta}$ term, qCEDM & $\Xi_{1,8}$.



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

Nucleon EDM. $\bar{\theta}$ term, qCEDM & $\Xi_{1,8}$.



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

$\mathbf{F_0}(\mathbf{q}^2)$

- purely short-distance
- momentum independent

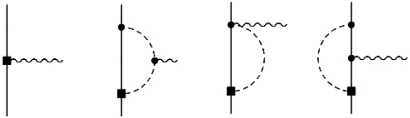
$\mathbf{F_1}(\mathbf{q}^2)$

- short-distance & charged pions in the loops

  $\bar{g}_0$ only relevant π-N coupling!

$\boxed{\text{nucleon EDFF cannot distinguish between Theta Term, qCEDM \& } \Xi_{1,8}}$

Nucleon EDM. $\bar{\theta}$ term, qCEDM & $\Xi_{1,8}$.



Leading Order

- F_0 purely short-distance & momentum independent

$$d_0 = \bar{d}_0 \qquad S'_0 = 0$$

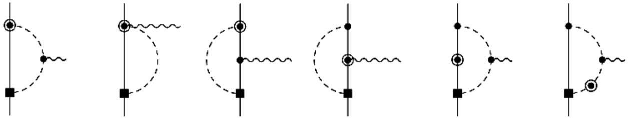
- pion loop contribute to d_1 & S'_1

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

$$S'_1 = \frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2}\frac{1}{6 m_\pi^2}$$

LO: R. Crewther *et al.*, '79, W. Hockings and U. van Kolck, '05.

Nucleon EDM. $\bar{\theta}$ term, qCEDM & $\Xi_{1,8}$.



Next-to-Leading Order

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

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

- recoil corrections to F_1

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

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

LO: R. Crewther *et al.*, ‘79, W. Hockings and U. van Kolck, ‘05.

NLO: Ottnad *et al.*, ‘09, EM *et al.*, ‘10

- EDM depends on $\bar{g}_0$, and short-distance LECs $\bar{d}_{0,1}$
- neutron EDM

$$|d_n| = |d_0 - d_1| \gtrsim \frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2}\left[\ln\frac{m_N^2}{m_\pi^2} + \frac{\pi}{2}\frac{m_\pi}{m_N}\right] \qquad \simeq (0.13 + 0.01)\,\frac{\bar{g}_0}{F_\pi}\; e\,\mathrm{fm}$$

$$\simeq 2.2 \times 10^{-3}\;\bar{\theta}\; e\,\mathrm{fm}$$

- good convergence of perturbative series
- from bound on d_n, $\bar{\theta} \lesssim 10^{-10}$
- NLO bound on isoscalar EDM

$$|d_0| \gtrsim \frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2}\,\pi\,\frac{3 m_\pi}{4 m_N} \simeq 0.012\,\frac{\bar{g}_0}{F_\pi}\; e\,\mathrm{fm}$$

$$= 0.2 \times 10^{-3}\;\bar{\theta}\, e\,\mathrm{fm}.$$

- but no reason to drop the counterms, $\bar{d}_{0,1}$

Nucleon EDM. qCEDM & $\Xi_{1,8}$.

- qCEDM

$$|d_n| = |d_0 - d_1| \gtrsim \frac{e g_A \bar{g}_0}{(2\pi F_\pi)^2}\left[\ln\frac{m_N^2}{m_\pi^2} + \frac{\pi}{2}\frac{m_\pi}{m_N}\right] \simeq (0.13 + 0.01)\ \frac{\bar{g}_0}{F_\pi}\ e\,\mathrm{fm}$$

$$\simeq 1.6 \times 10^{-2}\ \tilde{\delta}_{0,3}\left(\frac{M_{QCD}}{M_{\not T}}\right)^2\ e\,\mathrm{fm}$$

- from current bound on d_n

$$|\tilde{\delta}_{0,3}|\left(\frac{\mathrm{TeV}}{M_{\not T}^2}\right)^2 \lesssim (5\cdot 10^2)^{-2}$$

... but in most models $\tilde{\delta}_{0,3} \ll 1$ ...

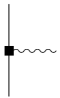
- FQLR: $\bar{g}_0 \sim \delta m_N$, a bit smaller than NDA

$$|d_n| \simeq 0.2|\xi|\left(\frac{M_{QCD}}{M_{\not T}}\right)^2 e\,\mathrm{fm} \Longrightarrow |\xi|\left(\frac{\mathrm{TeV}}{M_{\not T}}\right)^2 \lesssim (10^4)^{-2}$$

- factor of 10 weaker than in literature

H. An, X. Ji, F. Xu, '09

Nucleon EDM and EDFF. qEDM & χISs



- EDFF purely short-distance & momentum independent at LO
- EDFF acquires momentum dependence at NNLO

  - purely short distance for qEDM
  - with long distance component for χISs

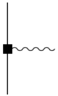
- isoscalar

$$F_0(\mathbf{q}^2) = d_0 = \bar{d}_0$$

- isovector

$$F_1(\mathbf{q}^2) = d_1 = \bar{d}_1$$

Nucleon EDM and EDFF. qEDM & χISs



- EDFF purely short-distance & momentum independent at LO
- EDFF acquires momentum dependence at NNLO

  - purely short distance for qEDM
  - with long distance component for χISs

- from NDA

$$|\delta_{0,3}| \left(\frac{\mathrm{TeV}}{M_{\not T}}\right)^2 \lesssim \left(5 \cdot 10^2\right)^{-2}, \qquad |w| \left(\frac{\mathrm{TeV}}{M_{\not T}}\right)^2 \lesssim \left(10^3\right)^{-2}$$

Nucleon EDM and EDFF. Sum up

Source	$\bar{\theta}$	qCEDM & $\Xi_{1,8}$	qEDM	χISs
$M_{\rm QCD}\, d_n/e$	$\mathcal{O}\left(\bar{\theta}\,\frac{m_\pi^2}{M_{\rm QCD}^2}\right)$	$\mathcal{O}\left(\tilde{\delta}\,\frac{m_\pi^2}{M_{\not T}^2}\right)$	$\mathcal{O}\left(\delta\,\frac{m_\pi^2}{M_{\not T}^2}\right)$	$\mathcal{O}\left(w\,\frac{M_{\rm QCD}^2}{M_{\not T}^2}\right)$
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.

Theta Term & qCEDM

- 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

qEDM & χISs

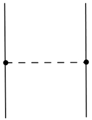
- $S_{1,0}'$ suppressed by m_π^2/M_{QCD}^2 with respect to d_i

Chiral Perturbation Theory. A $\geq$ 2

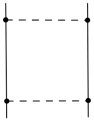
- another relevant scale:

  binding energy Q^2/m_N!

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



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



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

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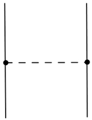
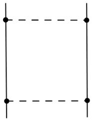


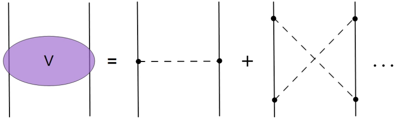
$$\sim \frac{g_A^2}{F_\pi^2}$$



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

Weinberg:

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

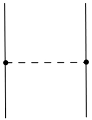


Chiral Perturbation Theory. A ≥ 2

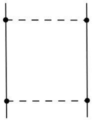
- another relevant scale:

  binding energy Q^2/m_N!

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



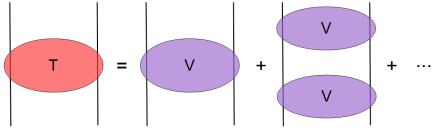
$$\sim \frac{g_A^2}{F_\pi^2}$$



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

Weinberg:

- "irreducible diagram":
  follow χPT power counting
  define the potential V
- amplitude: iterate V
  Lippmann-Schwinger equation!

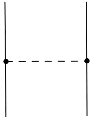


Chiral Perturbation Theory. A $\geq$ 2

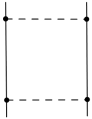
- another relevant scale:

  binding energy Q^2/m_N!

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



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



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

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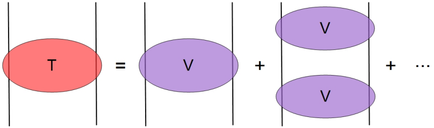


- "perturbative pions"

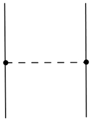
1. LO potential: contact S-wave operator (C_0)
2. pion exchange as perturbation: $Q/M_{NN} \ll 1$
3. $\gamma = \sqrt{m_N B}$ only relevant parameter in LO

Chiral Perturbation Theory. A $\geq$ 2

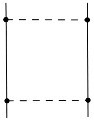
- another relevant scale:

  binding energy Q^2/m_N!

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



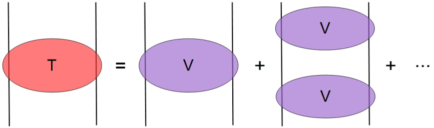
$$\sim \frac{g_A^2}{F_\pi^2}$$



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

Weinberg:

- "irreducible diagram":
  follow χPT power counting
  define the potential V
- amplitude: iterate V
  Lippmann-Schwinger equation!

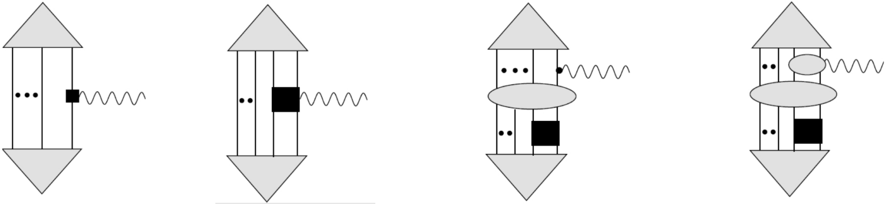


- "perturbative pions"
- "non-perturbative pions"

1. pion exchange leading effect

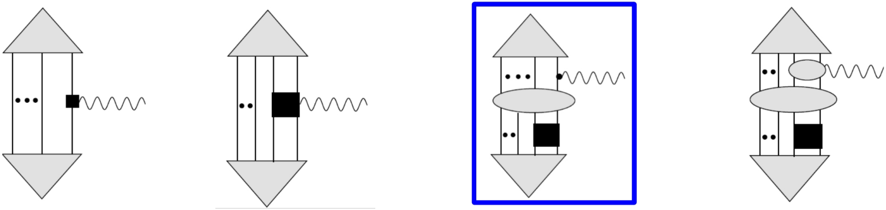
   $Q/M_{NN} \sim 1$

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



$$d_{0,1}$$

$$\frac{\bar{g}_0}{m_N^2}\,\frac{Q}{M_{NN}}$$

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

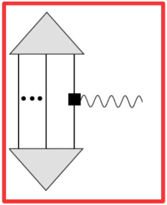
$$\frac{\bar{g}_{0,1}}{m_N^2}\,\frac{Q^2}{M_{NN}^2}$$

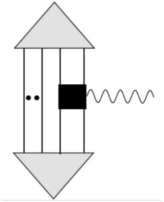
- extra loop cost no suppression (small suppression): $\frac{Q}{M_{NN}}$ vs $\frac{Q^2}{M_{QCD}^2}$
- pion-exchange dominates for chiral breaking sources

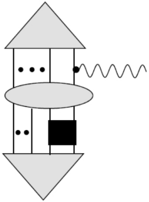
selection rules!

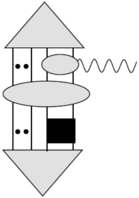
- light nuclei EDMs enhanced w.r.t d_n, d_p

EDMs of Light Nuclei. Power Counting







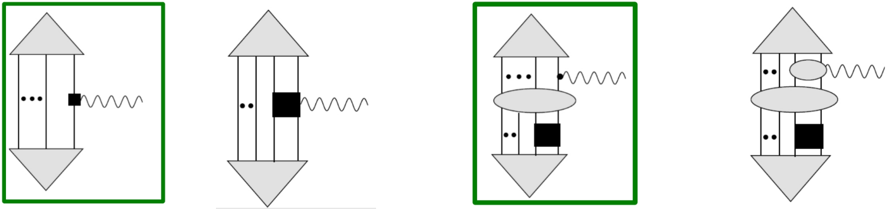


$d_{0,1}$ $\qquad$ $\dfrac{\bar{g}_0}{m_N^2}\,\dfrac{Q}{M_{NN}}$ $\qquad$ $\dfrac{\bar{g}_{0,1}}{Q^2}, \bar{C}_{1,2}F_\pi^2 \times \dfrac{Q}{M_{NN}}$ $\qquad$ $\dfrac{\bar{g}_{0,1}}{m_N^2}\,\dfrac{Q^2}{M_{NN}^2}$

- for qEDM one-body contribution dominates
- no substantial deviation from d_n, d_p

- for χISs, all contribs. should be considered
- with slight dominance of one-body piece

EDMs of Light Nuclei. Power Counting



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

- for qEDM one-body contribution dominates
- no substantial deviation from d_n, d_p

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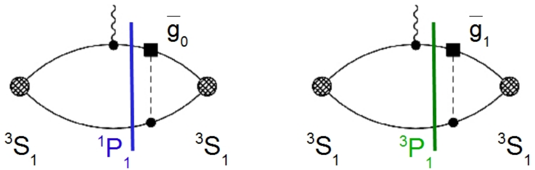
Deuteron EDM and MQM

Spin 1, Isospin 0 particle

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

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 and MQM

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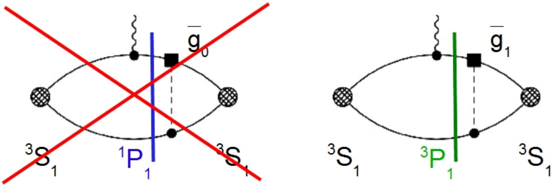

dEDM

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dMQM

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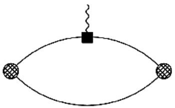
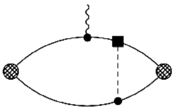
Deuteron EDM

One-body



TV corrections to wavefunction



"perturbative pions": expand in γ/M_{NN}, $\gamma = 45$ MeV

- only sensitive to isoscalar nucleon EDM

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

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

$$\begin{aligned} F_D(\mathbf{q}^2) &= -\frac{2}{3} e \frac{g_A \bar{g}_1}{m_\pi^2} \frac{m_N m_\pi}{4\pi F_\pi^2} \frac{1+\xi}{(1+2\xi)^2} \left(1 - 0.45 \left(\frac{|\mathbf{q}|}{4\gamma}\right)^2 + \ldots\right), \qquad \xi = \frac{\gamma}{m_\pi} \\ &= -0.23 \frac{\bar{g}_1}{F_\pi}\, e\,\mathrm{fm} + \mathcal{O}(\mathbf{q}^2) \end{aligned}$$

J. de Vries, *et al*, '11

Deuteron EDM. Non perturbative results

Iterate pions: $\gamma/M_{NN} \sim 1$

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

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

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

for AV18, C. P. Liu and R. Timmermans, '04; J. de Vries, et al, '12

- different potentials agree at the 10% level

I.R. Afnan and B. Gibson, '10; J. Bsaisou, *et al.*, '12;

- good agreement with the perturbative calculation

Deuteron EDM. $\bar{\theta}$ term, qCEDM & $\Xi_{1,8}$

Source	qCEDM $\times M_{\not T}^2/M_{QCD}^2$	$\Xi_{1,8} \times M_{\not T}^2/M_{QCD}^2$	$\bar{\theta}$ term
d_d	$(0.5 + 1.7) \cdot 10^{-2}\,\tilde{\delta}$	$(0.3 + 1.1)\,\tilde{\xi}$	$(5 + 0.3) \cdot 10^{-3}\,\bar{\theta}$

qCEDM & $\Xi_{1,8}$

- $\bar{g}_1$ is leading, deuteron mainly two-body
- d_0 about 30 % correction

$\boxed{d_d \gtrsim 2d_0}$

$\bar{\theta}$ term

- d_d well approximated by $2d_0$
  10% corrections from $\bar{g}_1$

$\boxed{d_d = 2d_0}$

Accuracy of the calculation:

- qCEDM: $\not P \not T$ potential and currents up to NLO $\lesssim 10\%$
- $\Xi_{1,8}$: 3π vertex contributes at NLO, $\pi Q/M_{QCD} \sim 30\%$
  not in the calculation yet!
- $\bar{\theta}$: other formally LO pieces are small.

Source $\times M_{\not T}^2/M_{QCD}^2$	qEDM	χISs
d_d	$(0.5 + 10^{-3}) \cdot 10^{-2}\,\delta$	$(0.34 + 0.02)\,w$

qEDM

- $\bar{g}_1$ suppressed by $\alpha_{\rm em}$
- d_d purely one-body

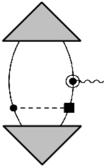
χISs

- $\bar{g}_1$ & d_0 same order
- $\bar{g}_1$ contribs. suppressed by γ/M_{NN}

$$\boxed{d_d = 2d_0}$$

- conclusion based on NDA. Need to do better!

Deuteron MQM. Theta Term.



$$m_d \mathcal{M}_d = -\left[0.30(1+\kappa_1)\frac{\bar{g}_1}{F_\pi} + 0.42(1+\kappa_0)\frac{\bar{g}_0}{F_\pi}\right] e\,\mathrm{fm}$$
$$\approx -\left[2 \cdot 10^{-3} + 5 \cdot 10^{-3}\right] \bar{\theta}\; e\,\mathrm{fm}$$

$$(1+\kappa_1) = 4.7, \quad (1+\kappa_0) = 0.88$$

J. de Vries *et al.*, '12

- no one-body contamination
- $\bar{g}_1$ & $\bar{g}_0$ contributions roughly comparable — large κ_1 enhances $\bar{g}_1$
- enhanced w.r.t to the long-range contribution to deuteron EDM

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

- AV18, EFT potentials for TC interactions

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

- $d_{^3\mathrm{He}}$ and $d_{^3\mathrm{H}}$ depend on 6 TV coefficients

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

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

numbers for AV18 J. de Vries, *et al*, '12.

- different potentials agree at 25% for one-body & pion-exchange contribs.
- no agreement for short range contribution ($\bar{C}_{1,2}$)

  for EFT potential, $\bar{C}_{1,2}$ contribs. five time bigger

- short-distance not treated consistently,
  need fully consistent calculation for χISs!
- ... but $\bar{C}_{1,2}$ small correction

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

$$\frac{d_{^3\mathrm{H}} - d_{^3\mathrm{He}}}{2} = 0.95\, d_1 + 0.15 \frac{\bar{g}_0}{F_\pi}\, e\,\mathrm{fm}$$

$$\frac{d_{^3\mathrm{H}} + d_{^3\mathrm{He}}}{2} = 0.85\, d_0 - 0.28 \frac{\bar{g}_1}{F_\pi}\, e\,\mathrm{fm}$$

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

$$\frac{d_{^3\mathrm{H}} - d_{^3\mathrm{He}}}{2} = (1.8 \cdot 10^{-3} + 2.2 \cdot 10^{-3})\, \bar{\theta}\, e\, \mathrm{fm}$$

$$\frac{d_{^3\mathrm{H}} + d_{^3\mathrm{He}}}{2} = (2.0 \cdot 10^{-3} + 0.2 \cdot 10^{-3})\, \bar{\theta}\, e\, \mathrm{fm}$$

- isovector EDM significantly different from d_1

but $\bar{g}_0$ less important than expected from NDA

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

$$\frac{d_{^3\mathrm{H}} - d_{^3\mathrm{He}}}{2} = (1.8 \cdot 10^{-3} + 2.2 \cdot 10^{-3})\ \bar{\theta}\, e\, \mathrm{fm}$$
$$\frac{d_{^3\mathrm{H}} + d_{^3\mathrm{He}}}{2} = (2.0 \cdot 10^{-3} + 0.2 \cdot 10^{-3})\ \bar{\theta}\, e\, \mathrm{fm}$$

- isovector EDM significantly different from d_1

  but $\bar{g}_0$ less important than expected from NDA

- $\bar{g}_1$ gives 10 % correction to isoscalar EDM

$\boxed{\text{smallness of } \bar{g}_0 \text{ \& nuclear matrix element increases importance of one-body!}}$

in agreement with ptb. counting

EDM of ^{3}He and ^{3}H. Dimension 6 Sources.

$$\frac{d_{^3\mathrm{H}} - d_{^3\mathrm{He}}}{2} = 0.95\, d_1 + \left(0.15 \frac{\bar{g}_0}{F_\pi} + 0.01 F_\pi^3 \bar{C}_1 - 0.02 F_\pi^3 \bar{C}_2 \right) e\,\mathrm{fm}$$

$$\frac{d_{^3\mathrm{H}} + d_{^3\mathrm{He}}}{2} = 0.85\, d_0 - 0.28 \frac{\bar{g}_1}{F_\pi}\, e\,\mathrm{fm}$$

Source	qCEDM	qEDM	χISs
$(d_{^3\mathrm{H}} - d_{^3\mathrm{He}})/2$	$(1 + 1.3) \cdot 10^{-2}\, \tilde{\delta}$	$0.2 \cdot 10^{-2}\, \delta$	$(0.17 + 0.01 + 0.005)\, w$
$(d_{^3\mathrm{H}} + d_{^3\mathrm{He}})/2$	$(0.2 + 2.5) \cdot 10^{-2}\, \tilde{\delta}$	$0.2 \cdot 10^{-2}\, \delta$	$(0.14 + 0.02)\, w$

qCEDM

- both isoscalar and isovector significantly different from $d_{0,1}$
- $\bar{g}_0$ and d_1 roughly equally important,
- $\bar{g}_1$ dominate, 10% correction from d_0

qEDM & χISs

- no deviation from $d_{0,1}$

but large uncertainty in $\bar{C}_{1,2}$ contrib.

to do: $\Xi_{1,8}$

- qualitatively similar to qCEDM
- **but** three-body TV force at LO

EDM of Light Nuclei. Summary

Source	$\bar{\theta}$	qCEDM & $\Xi_{1,8}$	qEDM	χISs
d_n	$\mathcal{O}\left(\bar{\theta}\frac{m_\pi^2}{M_{QCD}^3}\right)$	$\mathcal{O}\left(\tilde{\delta}\frac{m_\pi^2}{M_{QCD}M_{\not T}^2}\right)$	$\mathcal{O}\left(\delta\frac{m_\pi^2}{M_{QCD}M_{\not T}^2}\right)$	$\mathcal{O}\left(w\frac{M_{QCD}}{M_{\not T}^2}\right)$
d_d/d_n	$\mathcal{O}(1)$	$\mathcal{O}(10)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$m_d\mathcal{M}_d/d_d$	$\mathcal{O}(10)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$(d_{^3\mathrm{H}} - d_{^3\mathrm{He}})/d_n$	$\mathcal{O}(10)$	$\mathcal{O}(10)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$(d_{^3\mathrm{H}} + d_{^3\mathrm{He}})/d_n$	$\mathcal{O}(1)$	$\mathcal{O}(10)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$

Chiral & Isospin-breaking sources

- light nuclei dominated by OPE
- large deviation from d_n, d_p for deuteron, three-nucleon

Chiral breaking & Isoscalar source

- $\bar{g}_0$ important, $\bar{g}_1$ small
- significant deviation from d_n, d_p for $d_{^3\mathrm{H}} - d_{^3\mathrm{He}}$

Chiral invariant & EM sources

- no deviation from d_n, d_p

Summary & Conclusion

EFT approach

1. consistent framework to treat 1, 2, and 3 nucleon TV observables
2. qualitative relations between 1, 2, and 3 nucleon observables, specific to TV source
3. particularly promising for qCEDM, $\Xi_{1,8}$ and Theta Term

identify/exclude them in next generation of experiments?

4. not much hope to distinguish between qEDM and χISs

other observables? TV observables w/o photons?

To-do list

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

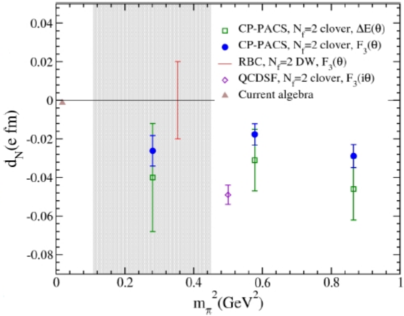
- compute LECs on the lattice
- NLO with perturbative pions
- fully consistent non ptb. calculation for ^{3}He, ^{3}H
- three-body force for $\Xi_{1,8}$
- study atomic EDMs

Backup Slides

Lattice Evaluation of the Nucleon EDM

Theta Term

- $\sim$ 10 times bigger than χPT result
- still large error, large m_π
- EDFF mainly isovector



from: Eigo Shintani, talk at Project X Physics Study, June '12.

Dimension 6 sources: some preliminary work on qEDM

see: T. Bhattacharya, talk at Project X Physics Study, June '12.

Lattice Evaluation of the Nucleon EDM

Theta Term

- ~ 10 times bigger than χPT result
- still large error, large m_π
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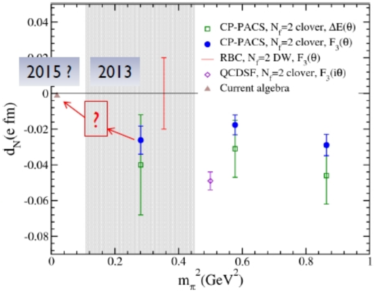


from: Eigo Shintani, talk at Project X Physics Study, June ‘12.

Dimension 6 sources: some preliminary work on qEDM

see: T. Bhattacharya, talk at Project X Physics Study, June ‘12.

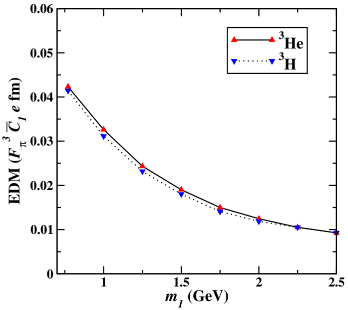
Helion & Triton EDM. Details

- no core shell model:
  $\Omega = 20,\ 30,\ 40,\ 50$ MeV,
  $N_{max} = 50$
- PT potentials
  AV18, EFT
  NN interaction @ N^{3}LO, p

  Entem and Machleidt, '03

  NNN interaction @ N^{2}LO

  Epelbaum *et al*, '02



For EFT potential:

- $N_{max} = 40$
- still linear dependence on $m_{1,2}$ at $m_{1,2} \sim 2.5$ GeV

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 $c^{(3)}_{3,\,\mathrm{em}}$

$\boxed{\text{no } T\text{-conserving observable constrains short distance contrib. to nucleon EDM}}$

- 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

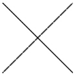
T-even sector

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

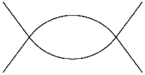
- enhance C_0 to account for unnaturaly large scattering lengths. In PDS scheme

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

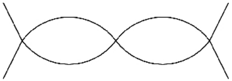
- iterate C_0 at all orders



C_0



$C_0 \, \frac{m_N Q}{4\pi} C_0$



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

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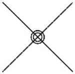
$$\mathcal{L}_{f=4} = -C_0^{^3S_1}(N^tP^iN)^\dagger N^tP^iN + \frac{C_2^{^3S_1}}{8}\left[(N^tP_iN)^\dagger N^t\mathbf{D}_-^2 P_iN + \mathrm{h.c.}\right] + \ldots, \qquad P^i = \frac{1}{\sqrt{8}}\sigma_2\sigma_i\tau_2$$

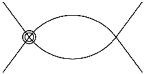
- enhance C_0 to account for unnaturaly large scattering lengths. In PDS scheme

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

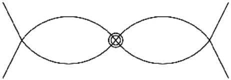
- iterate C_0 at all orders
- operators which connect S-waves get enhanced $C_2^{^3S_1} = \mathcal{O}\left(\frac{4\pi}{m_N\Lambda_{NN}}\frac{1}{\mu^2}\right)$



$C_0\frac{Q}{\Lambda_{NN}}$



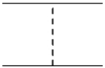
$C_0\frac{Q}{\Lambda_{NN}}\ \frac{m_NQ}{4\pi}C_0$



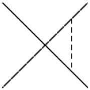
$C_0\frac{Q}{\Lambda_{NN}}\ \left(\frac{m_NQ}{4\pi}C_0\right)^2$

Deuteron EDM and MQM. KSW Power Counting

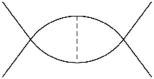
- treat pion exchange as a perturbation



$C_0 \frac{g_A^2 m_N Q}{4\pi F_\pi^2}$



$C_0 \frac{g_A^2 m_N Q}{4\pi F_\pi^2} \, \frac{m_N Q}{4\pi} C_0$



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

- 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 $Q \sim m_\pi$

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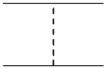
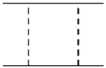


$\frac{g_A^2}{F_\pi^2}$



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

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

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

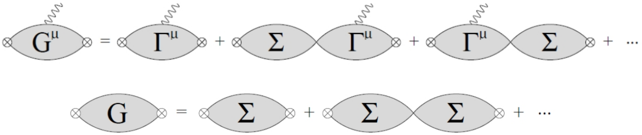
b. four-nucleon T-odd currents

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

- in the PDS scheme

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

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

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

- two-point function

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