P- and T-Odd Nuclear Moments

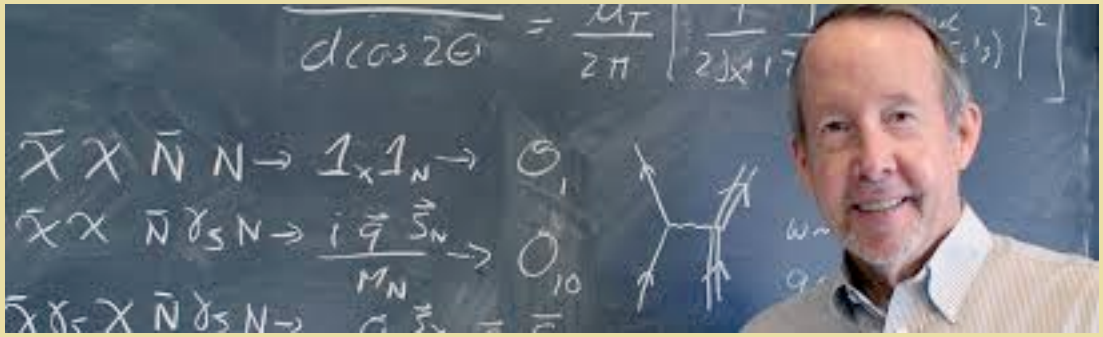
M.J. Ramsey-Musolf

- *T.D. Lee Institute & Shanghai Jiao Tong Univ.*
- *UMass-Amherst*

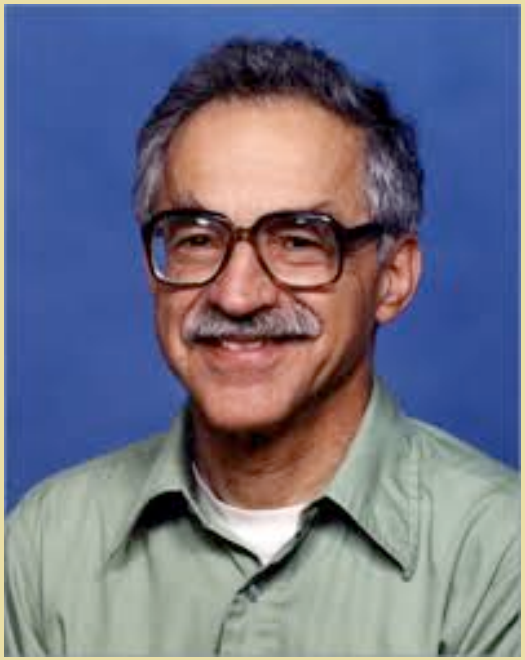
My pronouns: he/him/his

Haxton Fest, UC Berkeley / LBNL January 2020

Wick Haxton: Role Model & Mentor



Wick Haxton & Ernest Henley



1924-2017

8 Coauthored Papers

Outline

I. Context

II. Hadronic Parity Violation & the Anapole Moment

III. Anapole Moment & PV Electron Scattering

IV. Electric Dipole Moments (Briefly!)

V. Summary

I. Context

What is an Anapole Moment ?

Nuclear Moments

	PT	$\not{P}T$	$P\not{T}$	$\not{P}\not{T}$	
C_J	E	✖	✖	$\boxed{O}$	*EDM, Schiff…*
$T^M{}_J$	O	✖	✖	$\boxed{E}$	*MQM….*
$T^E{}_J$	✖	$\boxed{O}$	E	✖	*Anapole…*

Coulomb → C_J

Magnetic → $T^M{}_J$

Transverse electric → $T^E{}_J$

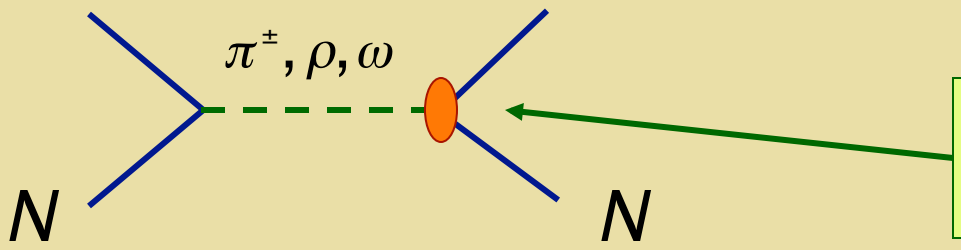
J=1

$$\vec{d} = \int d^3x\, \vec{x}\, \rho(\vec{x}) \qquad \vec{\mu} = \frac{1}{2}\int d^3x\, \vec{x} \times \vec{J}(\vec{x}) \qquad \vec{a} = \int d^3x\, x^2\, \vec{J}(\vec{x})$$

II. Hadronic PV & the Anapole Moment

$\Delta S = 0$ Hadronic Weak Interaction

Meson-exchange model

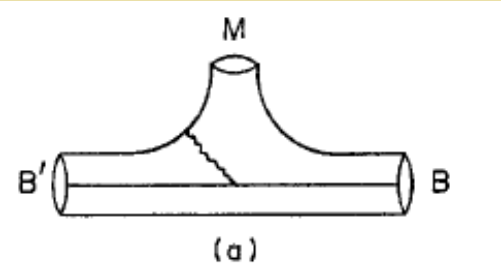


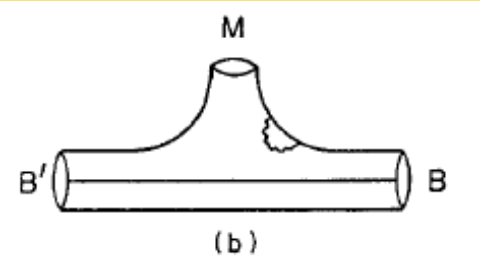
Seven PV meson-nucleon couplings

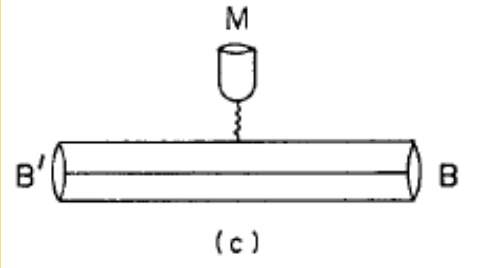
$$h_{\pi}^{1},\ h_{\rho}^{0,1,2},\ h_{\omega}^{0,1},\ h_{\rho}^{1\,\prime}$$

How to compute couplings from 4q interaction ?

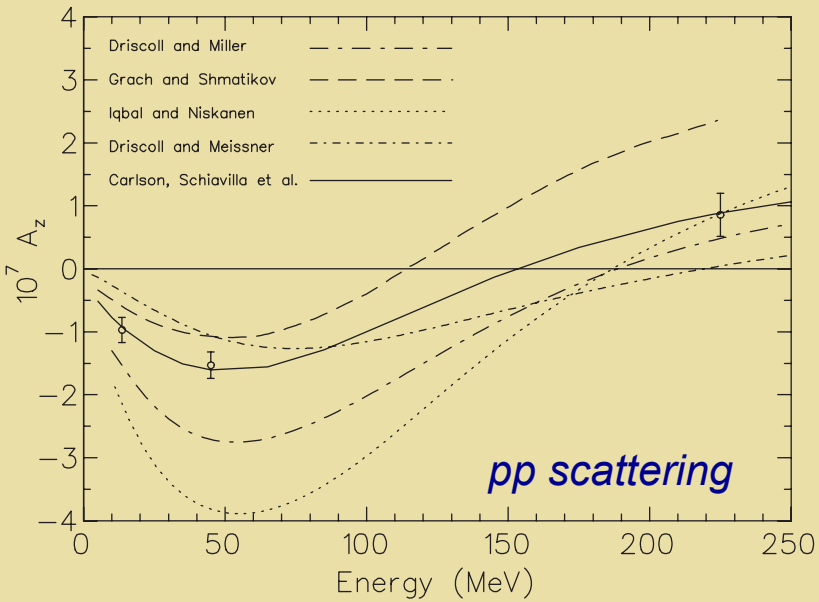
Desplanques, Donoghue, & Holstein (DDH): $SU(6)_w$ + Quark Model

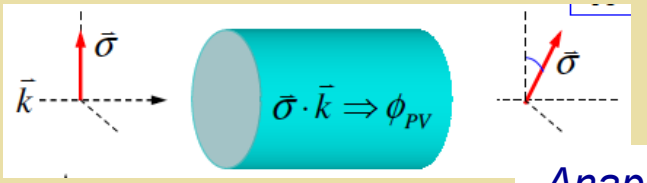




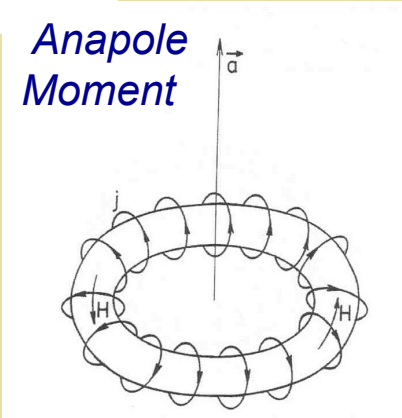


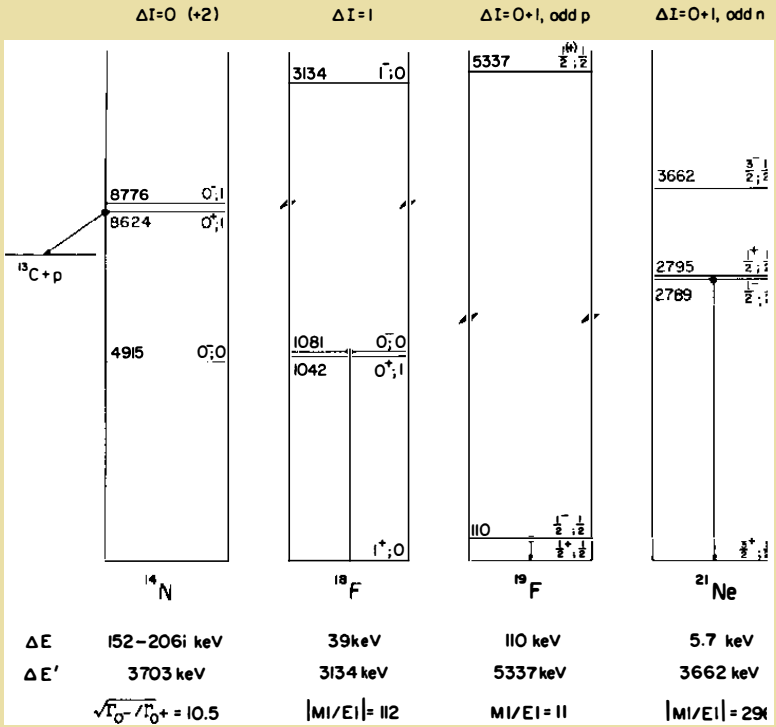
Observables





^{4}He spin rotation





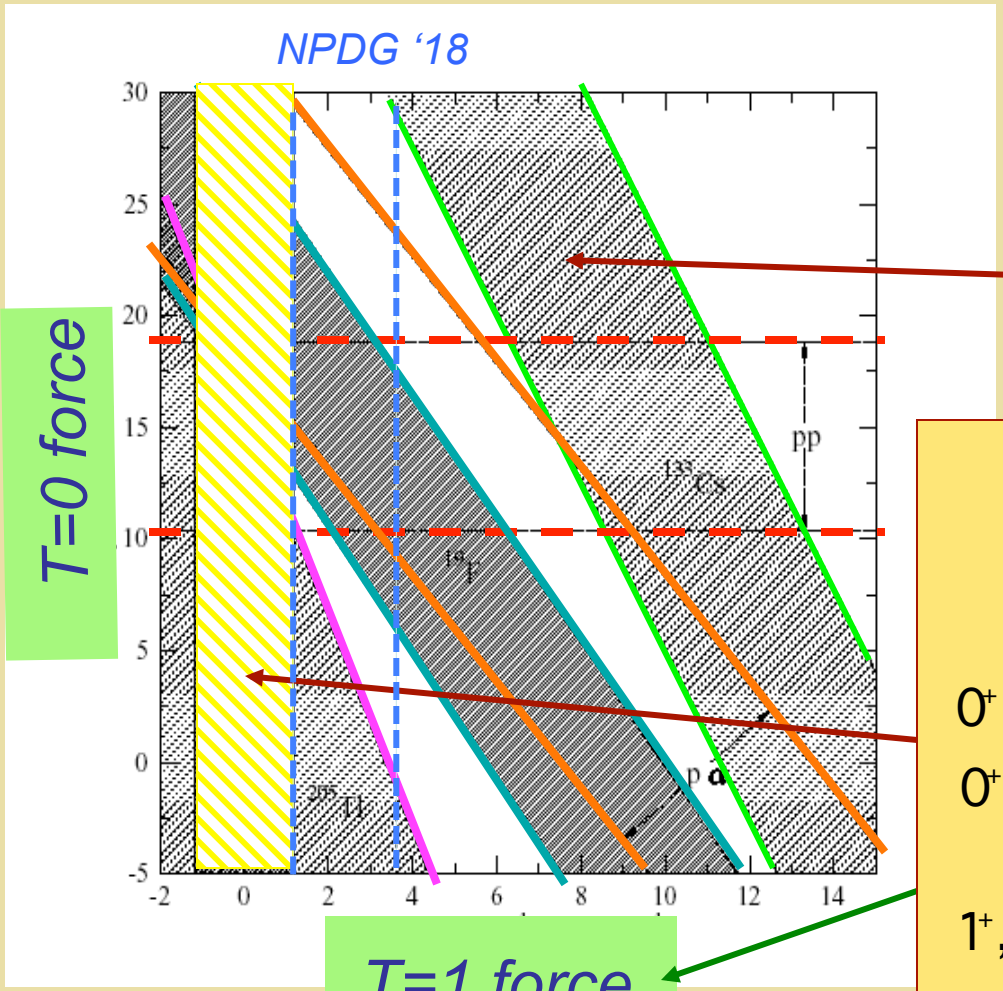
Light nuclei

Parity-doublets: nuclear amplifier

Adelberger & Haxton '85

S. Page & MJRM '06

$\Delta S = 0$ Hadronic Weak Interaction

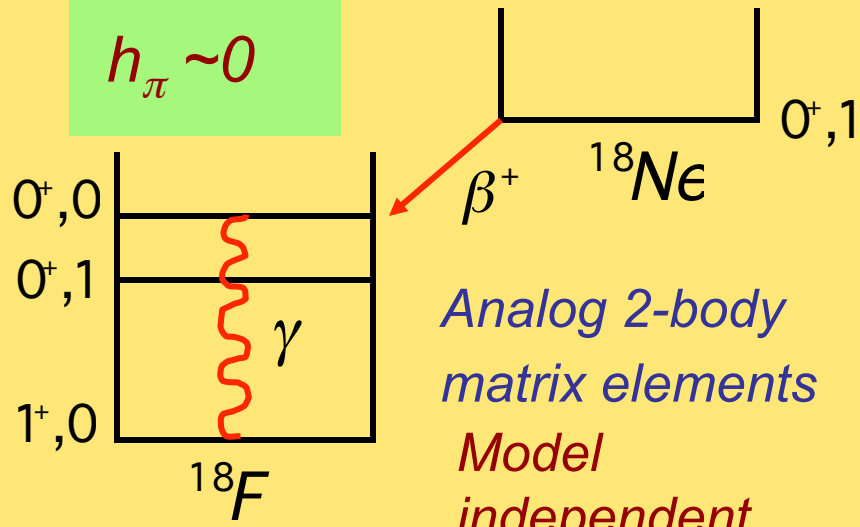


$h_\pi \sim 10\, g_\pi$

^{133}Cs Anapole moment

Boulder, atomic PV

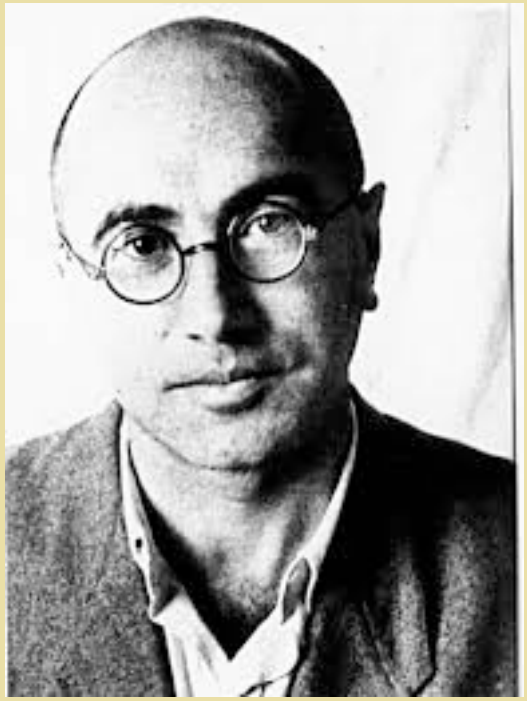
$h_\pi \sim 0$



Analog 2-body matrix elements

Model independent

Anapole Moment



1957

What is an Anapole Moment ?

$$\langle p'| J_\mu^{\mathrm{EM}} |p\rangle = \bar{U}(p')\left[F_1\gamma_\mu + \frac{iF_2}{2M}\sigma_{\mu\nu}q^\nu + \frac{iF_3}{2M}\sigma_{\mu\nu}\gamma_5 q^\nu + \frac{F_A}{M^2}(q^2\gamma_\mu - \not{q}q_\mu)\gamma_5\right]U(p)$$

F_1 :	Dirac (charge) form factor	P, T Conserving
F_2 :	Pauli (magnetic) ff	P, T Conserving
F_3 :	Electric Dipole ff	P, T Violating
F_A :	Anapole ff	P Violating

What is an Anapole Moment ?

Nuclear Moments

	PT	$\not{P}T$	$P\not{T}$	$\not{P}\not{T}$	
C_J	E	✖	✖	$\boxed{O}$	*EDM, Schiff…*
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Coulomb → C_J

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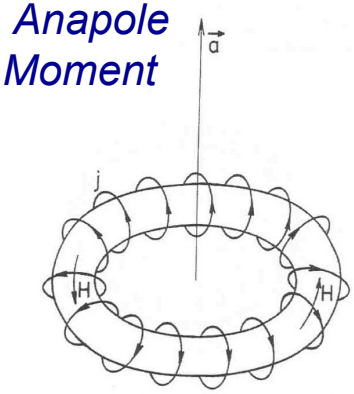
What is an Anapole Moment ?

Friar & Fallieros 1984: "Extended Siegert Theorem"

$$T^{\mathrm{el}}_{JM} = -\frac{q^{J-1}[(J+1)/J]^{1/2}}{(2J+1)!!} \times [H_0, \int d^3x\, x^J Y_{JM}(\hat{x}) g_J(qx) \rho(\vec{x})] + \frac{2q^{J+1}}{(J+2)(2J+1)!!} \int d^3x\, x^J \vec{Y}^M_{JJ} \cdot \vec{\mu}(\vec{x}) h_J(qx)$$

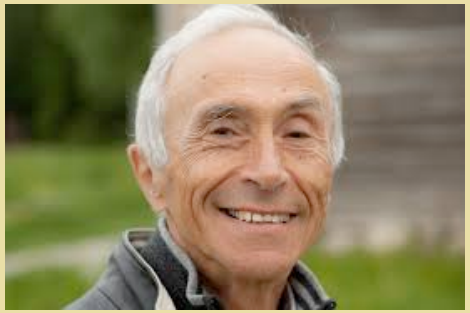
Anapole Moment



$$\langle \mathrm{g.s.} || E1 || \mathrm{g.s.} \rangle \underset{\mathbf{q}^2 \to 0}{=} -\frac{i\mathbf{q}^2}{9(6\pi)^{1/2}} \int d\mathbf{r}\, r^2 \langle \mathrm{g.s.} || \mathbf{j}_{\mathrm{em}}(\mathbf{r}) + (2\pi)^{1/2} [Y_2(\Omega_r) \otimes j_{\mathrm{em}}(\mathbf{r})]_1 || \mathrm{g.s.} \rangle$$

Haxton, Henley, MJRM 1989

How to Look for the Anapole Moment ?


On the Possibility to Study P Odd and T Odd Nuclear Forces in Atomic and Molecular Experiments
V.V. Flambaum, I.B. Khriplovich, O.P. Sushkov (Novosibirsk, IYF). Apr 1984. 44 pp.
Published in **Sov.Phys.JETP 60 (1984) 873**
IYF-84-85

Nuclear spin-dependent contribution to atomic PV

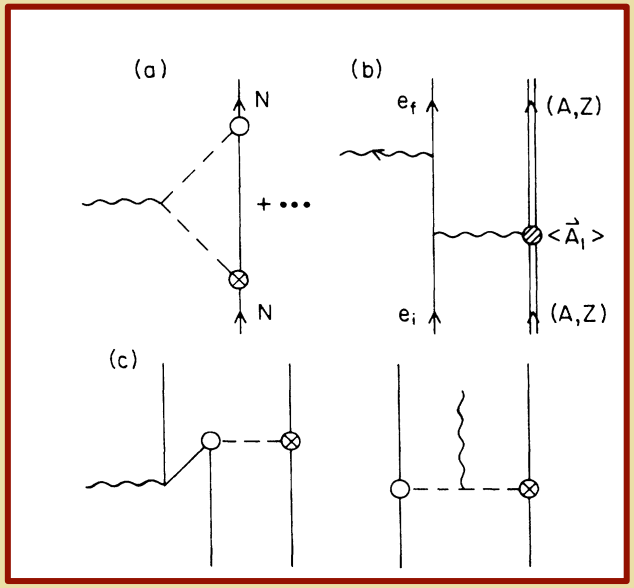
How to Compute the Anapole Moment ?

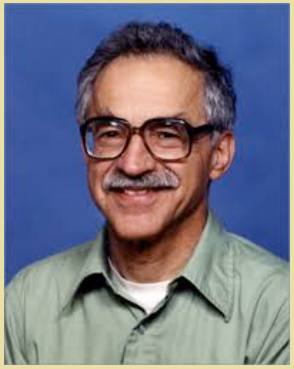
VOLUME 63, NUMBER 9 PHYSICAL REVIEW LETTERS 28 AUGUST 1989

Nucleon and Nuclear Anapole Moments

W. C. Haxton and E. M. Henley
Institute for Nuclear Theory, Department of Physics, FM-15, University of Washington, Seattle, Washington 98195

M. J. Musolf
Joseph Henry Laboratories, P.O. Box 708, Princeton University, Princeton, New Jersey 08544
(Received 1 May 1989)

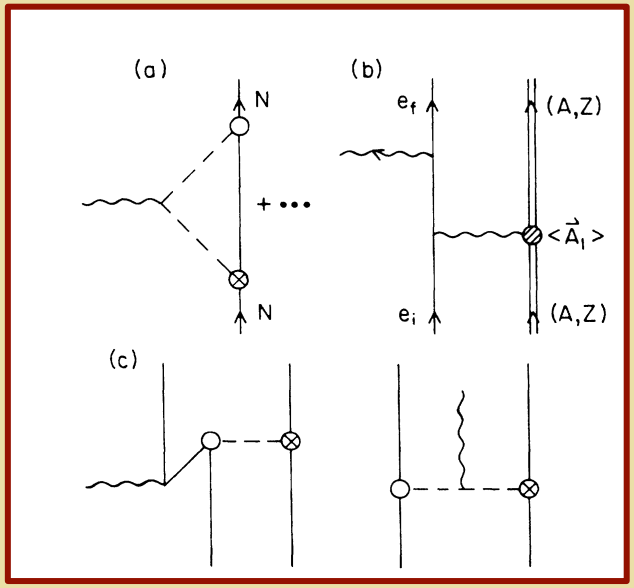


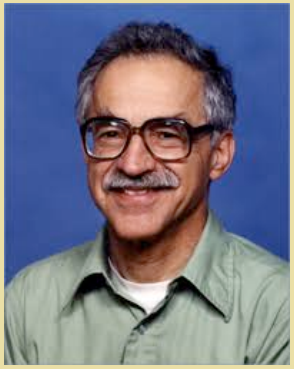


How to Compute the Anapole Moment ?

TABLE I. Shell-model estimates of the one-body, polarization, and exchange-current contributions to the anapole matrix element $\langle \text{g.s.} | \, |A_1| \, | \text{g.s.} \rangle$ in units of ef_π. The last column gives the ratio of the anapole interaction with an on-shell electron to that generated by Z^0 exchange, assuming $f_\pi = f_\pi^{\text{DDH}}$ and $\sin^2\theta_W = 0.23$.

Nucleus	One body	Polarization	$N\bar{N}$	Pionic	Total	V^{AN}/V^{Z^0}
^{19}F	0.55	20.03	1.79	−0.62	21.8	1.07
^{133}Cs	−0.58	−41.97	−9.90	0.76	−51.7	2.72





Is the Anapole Moment an Observable ?

PHYSICAL REVIEW D VOLUME 43, NUMBER 9 1 MAY 1991

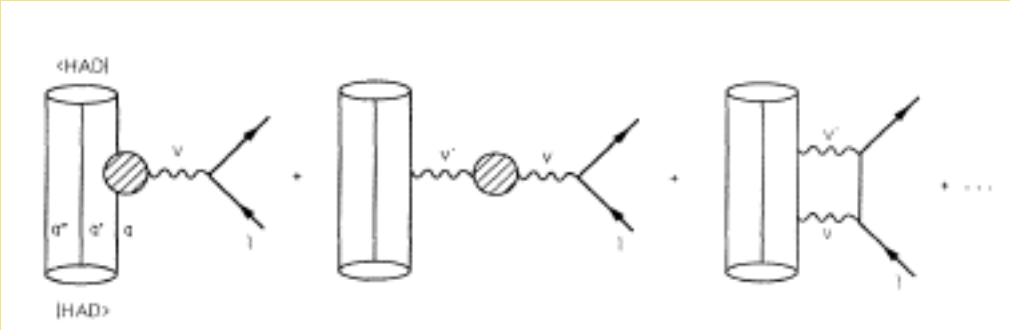
Observability of the anapole moment and neutrino charge radius

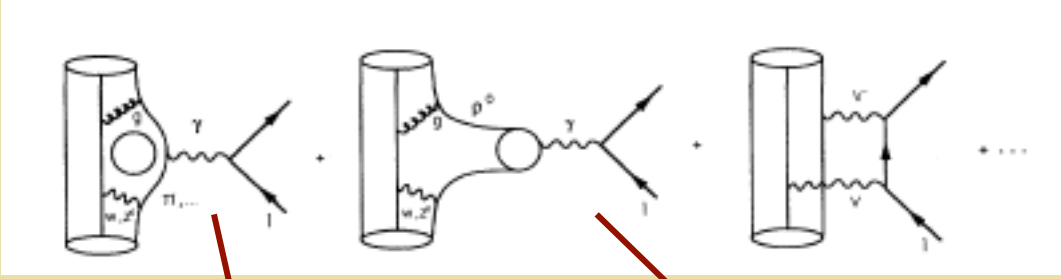
M. J. Musolf
Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

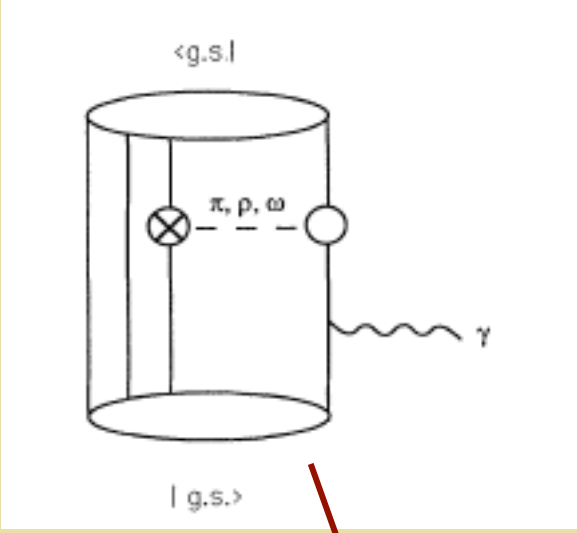
Barry R. Holstein
Department of Physics and Astronomy, University of Massachusetts, Amherst, Massachusetts 01003
(Received 25 September 1990)

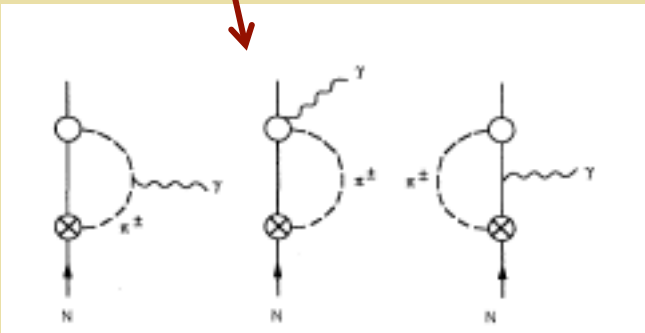
The properties of the neutrino charge radius (NCR) and anapole moments (AM's) of elementary fermions, nucleons, and nuclei are discussed. The dependence of these off-shell electromagnetic couplings on the weak gauge parameter is explicitly demonstrated by a calculation performed in the R_ξ gauge. The gauge dependence of the AM's and NCR implies that they cannot be observed in isolation from other second-order, electroweak effects. It is shown, however, that the AM's of various hadronic systems having an $SU(2)_L$ quantum number $T_3^L=0$ can be considered "observables" in certain formal, though unphysical, limits. It is argued that, apart from these special limits, the AM is a physically meaningful entity only for heavy and/or nearly degenerate nuclei.

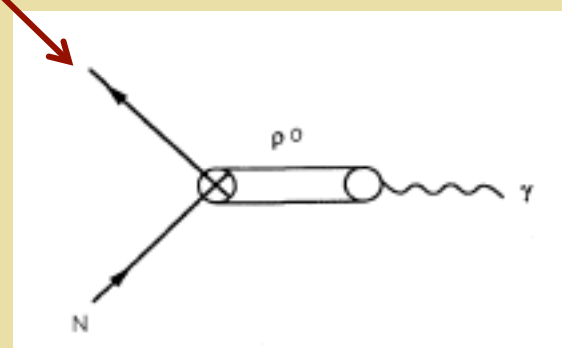
What is an Anapole Moment ?











$$|\vec{a}| \sim A^{2/3}$$

Holstein, MRM '90

Evidence for the Anapole Moment

SHARE

0

0

RESEARCH ARTICLE

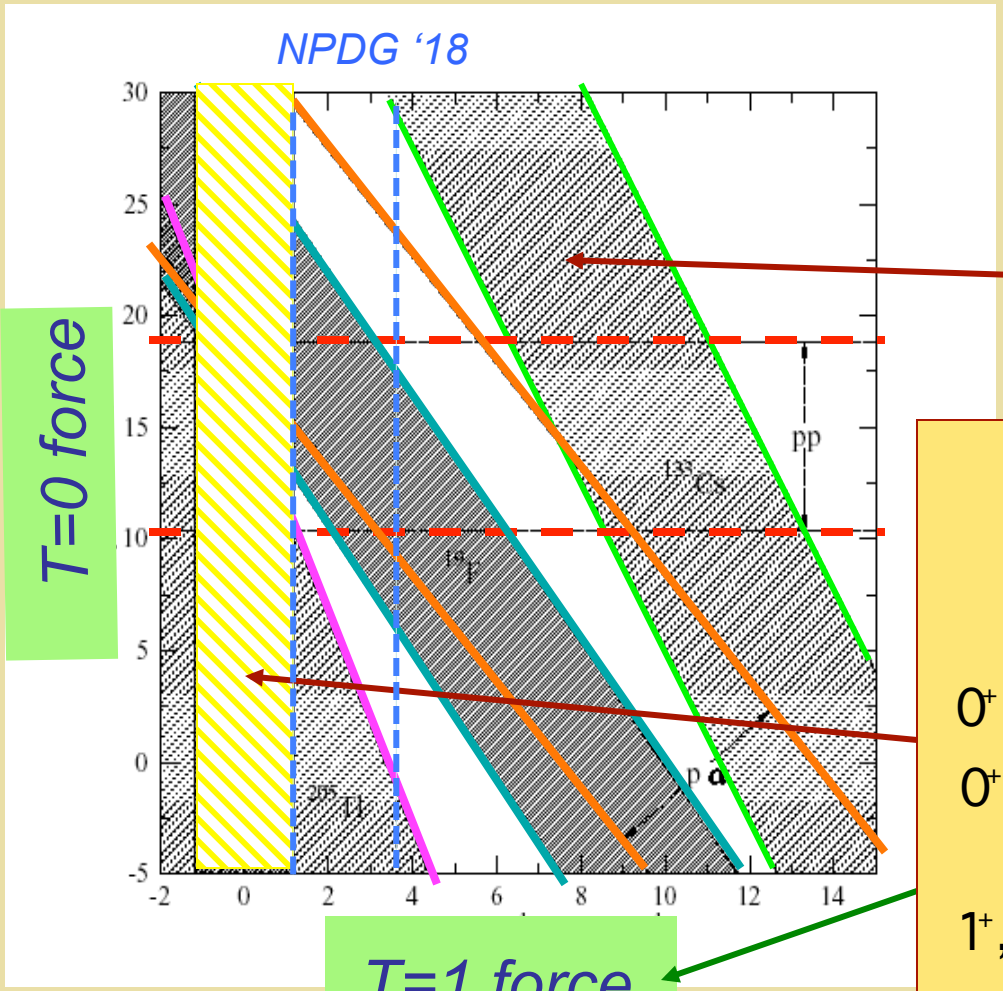
Measurement of Parity Nonconservation and an Anapole Moment in Cesium

C. S. Wood, S. C. Bennett, D. Cho*, B. P. Masterson†, J. L. Roberts, C. E. Tanner‡, C. E. Wieman§

+ See all authors and affiliations

Science 21 Mar 1997:
Vol. 275, Issue 5307, pp. 1759-1763
DOI: 10.1126/science.275.5307.1759

$\Delta S = 0$ Hadronic Weak Interaction

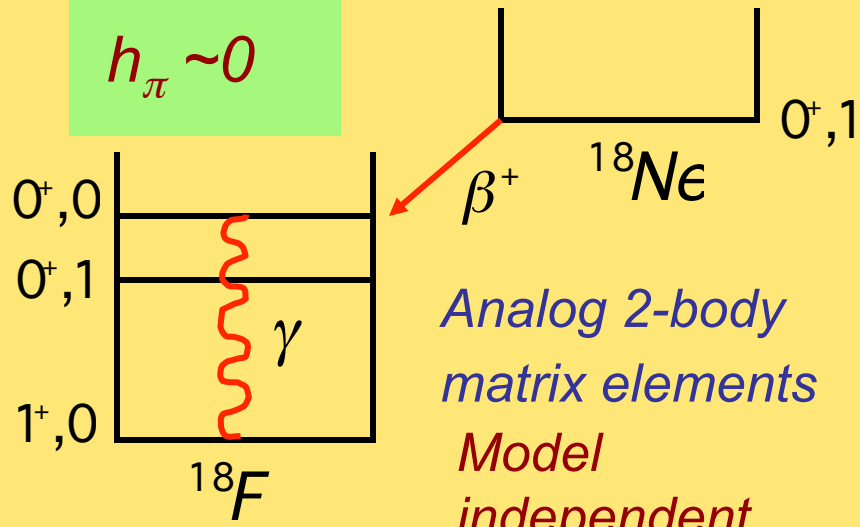


$h_\pi \sim 10\, g_\pi$

^{133}Cs Anapole moment

Boulder, atomic PV

$h_\pi \sim 0$

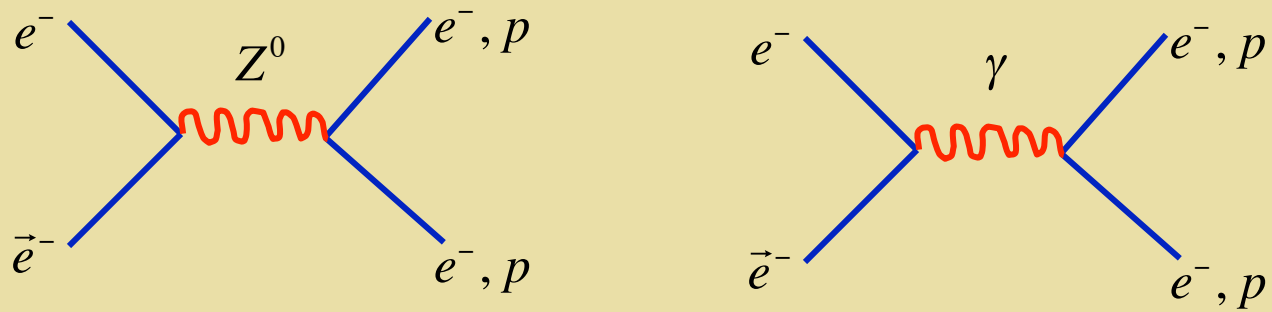


Analog 2-body matrix elements

Model independent

IV. The Anapole Moment & PVES

Parity-Violation & Nucleon Structure



Parity-Violating electron scattering

$$A_{PV} = \frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Q_W + F(Q^2,\theta)\right]$$

"Weak Charge" ~ 0.1 in SM

Enhanced transparency to new physics

Small QCD uncertainties (Marciano & Sirlin; Erler & R-M)

QCD effects (s-quarks): measured (MIT-Bates, Mainz, JLab)

Strange Quarks: G_M^P & G_E^P

Nuclear Physics B310 (1988) 527–547
North-Holland, Amsterdam

STRANGE MATRIX ELEMENTS IN THE PROTON FROM NEUTRAL-CURRENT EXPERIMENTS

David B KAPLAN[1]

Department of Physics, Harvard University, Cambridge, MA 02138, USA

Aneesh MANOHAR[2]

Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Received 19 May 1988

Strange Quarks: G_M^P & G_E^P

Volume 219, number 2,3 PHYSICS LETTERS B 16 March 1989

SENSITIVITY OF POLARIZED ELASTIC ELECTRON–PROTON SCATTERING TO THE ANOMALOUS BARYON NUMBER MAGNETIC MOMENT

R.D. McKEOWN
W.K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, CA 91125, USA

Received 20 August 1988

The anomalous baryon number magnetic moment may be a useful quantity in constraining various models of nucleon structure. It is shown that this quantity can be determined quite precisely in the elastic scattering of polarized electrons by unpolarized protons at low momentum transfer.

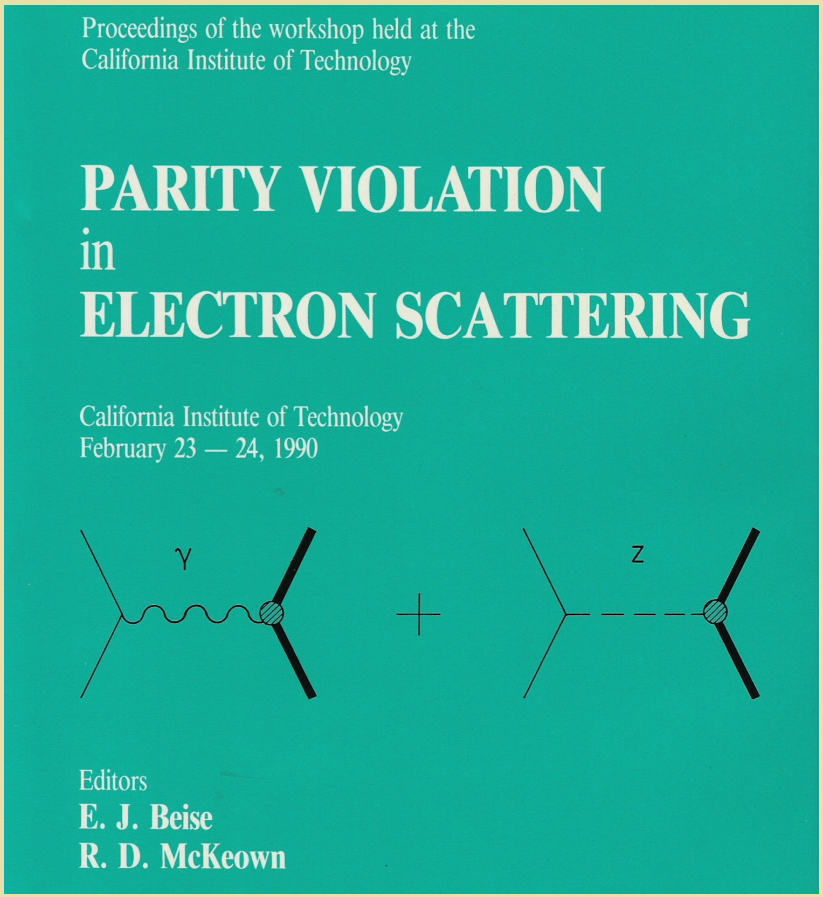
PHYSICAL REVIEW D VOLUME 39, NUMBER 11 1 JUNE 1989

Strange-quark vector currents and parity-violating electron scattering from the nucleon and from nuclei

D. H. Beck
W.K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
(Received 3 January 1989)

Measurements of the processes $p(\pi,\pi)$, $p(\nu,\nu)/p(\bar{\nu},\bar{\nu})$, and deep-inelastic $\vec{p}(\vec{\mu},\mu')$ can be interpreted in a manner which requires a significant strange-quark contribution to proton matrix elements. In this paper some implications of strange-quark contributions to proton vector currents and their manifestation in parity-violating electron-scattering experiments are examined. It is found that strange-quark currents of plausible magnitude significantly affect the parity-violating elastic electron scattering from the nucleon in certain kinematic regimes. It is also shown that, while the effects in on-going parity-violating experiments on ^{9}Be and ^{12}C are small, significant strange-quark contributions might be expected in experiments with nuclear targets at higher-momentum transfer.

Wick Haxton & Parity Violation



1990 Caltech Workshop


Generating theoretical activity

Strange Quarks: G_M^P & G_E^P

Interpreting the asymmetry

Nuclear Physics A546 (1992) 509–587
North-Holland

NUCLEAR PHYSICS A

The interpretation of parity-violating electron-scattering experiments*

M.J. Musolf and T.W. Donnelly

Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Received 3 February 1992

Strange Quarks: G_M^P & G_E^P

Interpreting the asymmetry

3.1.1. Backward angles. In the $\theta \to 180°$ limit, $\varepsilon \to 0$ and we have

$$\frac{W^{\mathrm{p.v.}}}{F^2} \to (1-4\sin^2\theta_W)(1+R_V^p) - \frac{1}{G_M^p}[(1+R_V^n)G_M^n + (1+R_V^{(0)})G_M^{(s)}] + \sqrt{\frac{1}{\tau}+1}(-1+4\sin^2\theta_W)\frac{\tilde{G}_A^p}{G_M^p}.$$

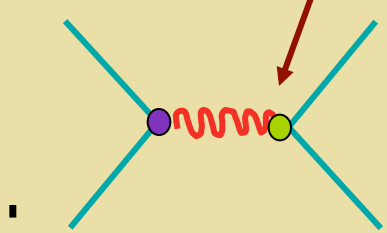
$$\tilde{G}_A^p = -g_A G_D^A[1+R_A^p+(1+R_A^{(0)})\eta], \qquad \eta = \frac{G_A^{(s)}(0)}{g_A}$$

Now called " G_A^e "

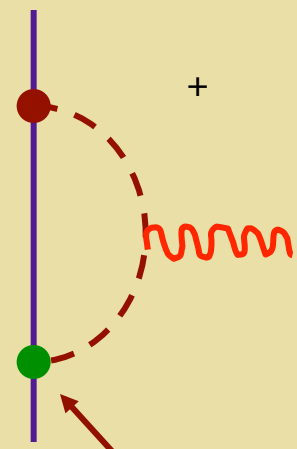
Strange axial current

Strange Quarks: Radiative Corrections

$$\tilde{G}_A^p = -g_A G_D^A[1 + R_A^p - (1 + R_A^{(0)})\eta], \qquad \eta = \frac{G_A^{(s)}(0)}{g_A}$$



$+ \cdots$

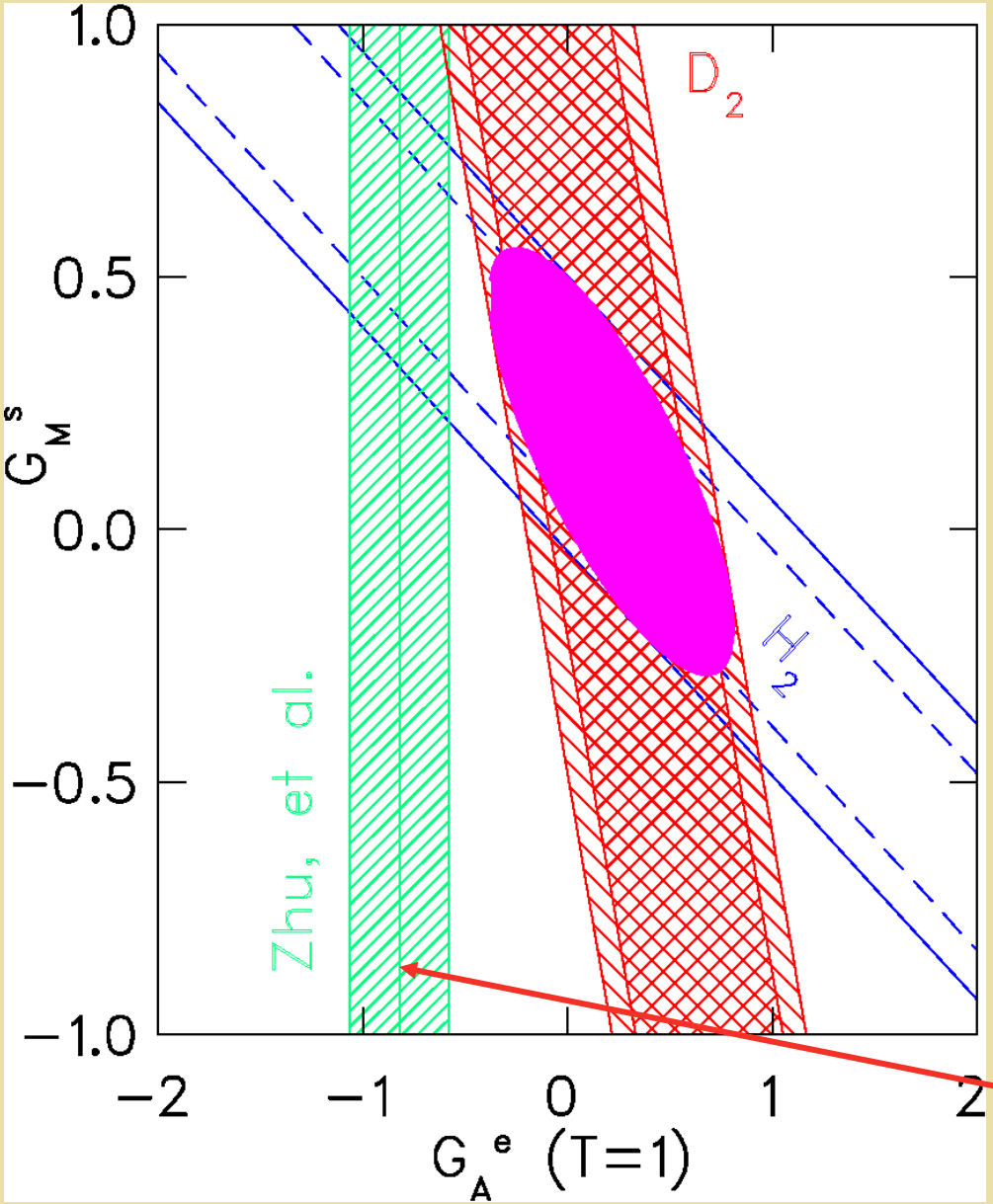


"Anapole"

Hadronic PV

SAMPLE Results

R. Hasty et al., Science 290, 2117 (2000).



at Q^2=0.1 (GeV/c)^2

- s-quarks contribute less than 5% (1σ) to the proton's magnetic moment.

Radiative corrections

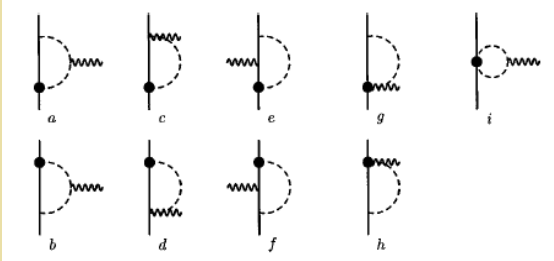
E. Beise, U Maryland

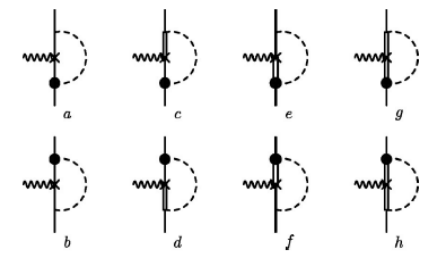
Strange Quarks: Radiative Corrections

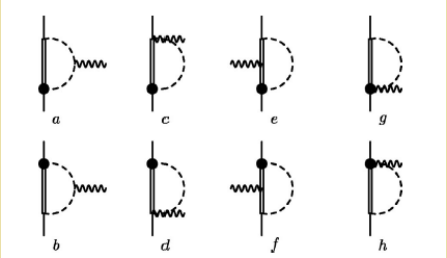
PHYSICAL REVIEW D, VOLUME 62, 033008

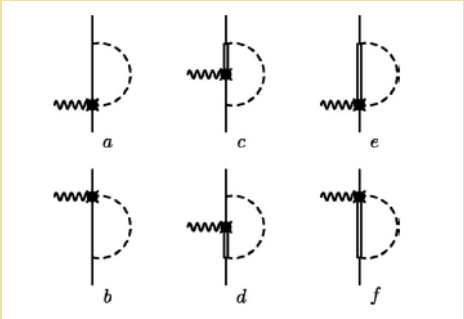
Nucleon anapole moment and parity-violating *ep* scattering

Shi-Lin Zhu,[1] S. J. Puglia,[1] B. R. Holstein,[3] and M. J. Ramsey-Musolf[1,2]
[1]*Department of Physics, University of Connecticut, Storrs, Connecticut 06269*
[2]*Theory Group, Thomas Jefferson National Laboratory, Newport News, Virginia 23606*
[3]*Department of Physics and Astronomy, University of Massachusetts, Amherst, Massachusetts 01003*
(Received 29 February 2000; published 12 July 2000)





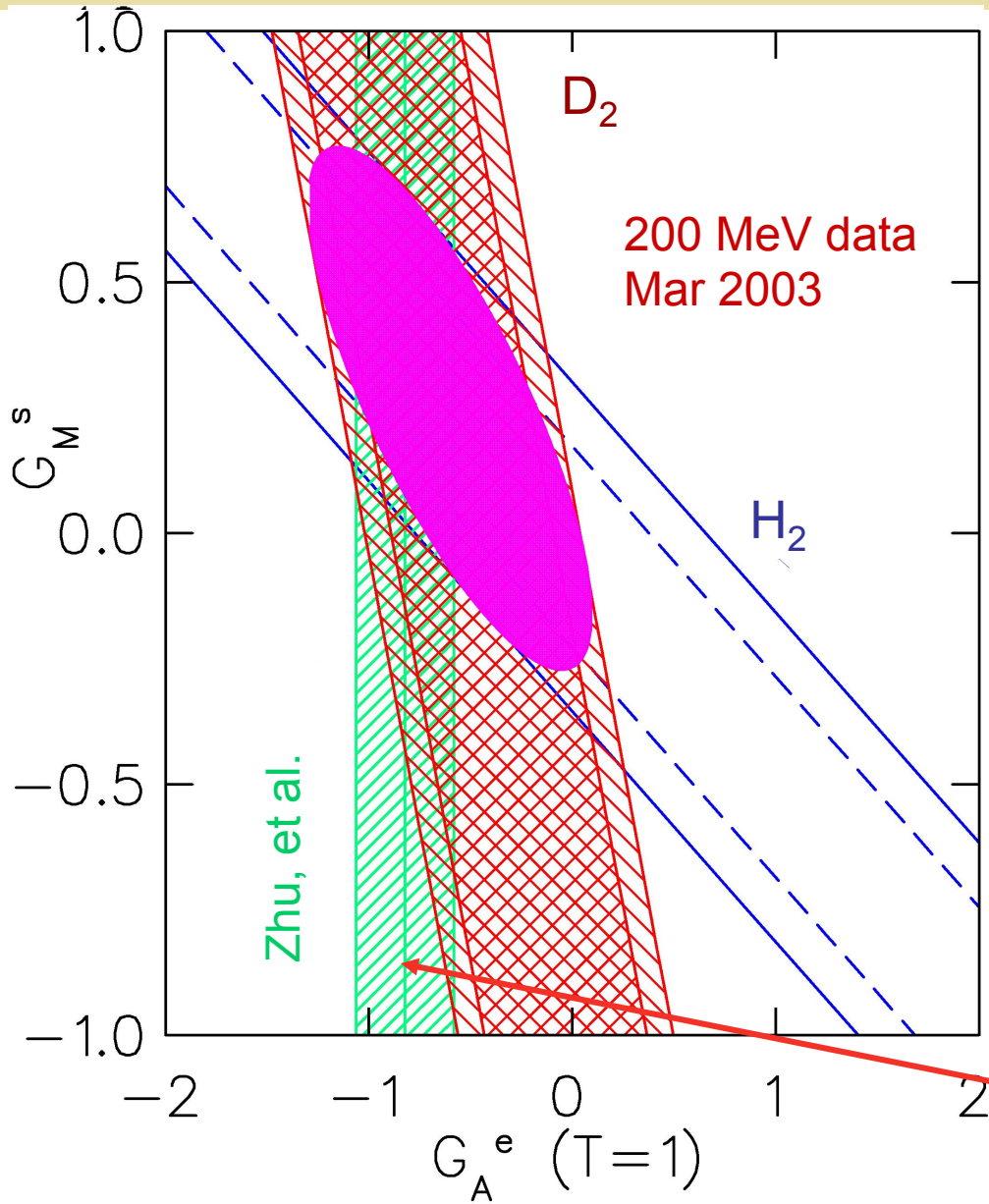




Source	$R_A^{T=1}$	$R_A^{T=0}$
One-quark (SM)	-0.35	0.05
Anapole	-0.06 ± 0.24	0.01 ± 0.14
Total	-0.41 ± 0.24	0.06 ± 0.14

SAMPLE Results

R. Hasty et al., Science 290, 2117 (2000).



at Q^2=0.1 (GeV/c)^2

- s-quarks contribute less than 5% (1σ) to the proton's magnetic moment.

200 MeV update 2003:
Improved EM radiative corr.
Improved acceptance model
Correction for π background

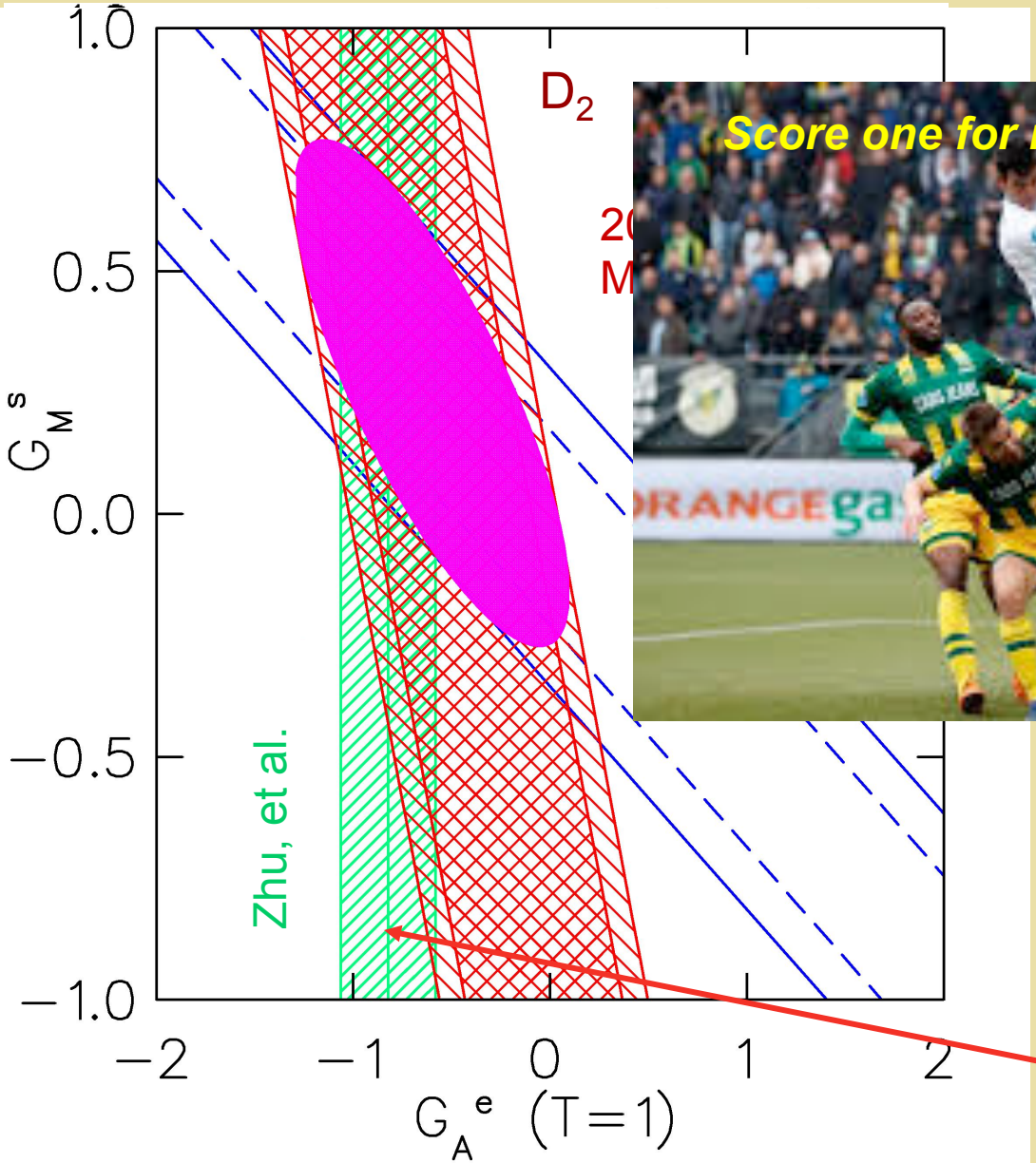
125 MeV:
no π background
similar sensitivity
to G_A^e(T=1)

Radiative corrections

E. Beise, U Maryland

SAMPLE Results

R. Hasty et al., Science 290, 2117 (2000).



at Q^2=0.1 (GeV/c)^2

ss

ent.

corr.
nodel
round

125 MeV:
no π background
similar sensitivity
to G_A^e(T=1)

Radiative corrections

E. Beise, U Maryland

IV. EDMs (Briefly)

What is an EDM ?

$$\langle p'| J_\mu^{\mathrm{EM}} |p\rangle = \bar{U}(p')\left[F_1\gamma_\mu + \frac{iF_2}{2M}\sigma_{\mu\nu}q^\nu + \frac{iF_3}{2M}\sigma_{\mu\nu}\gamma_5 q^\nu + \frac{F_A}{M^2}(q^2\gamma_\mu - \not{q}q_\mu)\gamma_5\right]U(p)$$

F_1 :	Dirac (charge) form factor	P, T Conserving
F_2 :	Pauli (magnetic) ff	P, T Conserving
F_3 :	Electric Dipole ff	P, T Violating
F_A :	Anapole ff	P Violating

P- and T-Odd Nuclear Moments

Nuclear Moments

Coulomb

Magnetic

Transverse electric

	PT	$\not{P}T$	$P\not{T}$	$\not{P}\not{T}$	
C_J	E	✖	✖	$\boxed{O}$	EDM, Schiff…
$T^M{}_J$	O	✖	✖	$\boxed{E}$	MQM….
$T^E{}_J$	✖	$\boxed{O}$	E	✖	Anapole…

J=1

$$\vec{d} = \int d^3x\, \vec{x}\, \rho(\vec{x})$$

$$\vec{\mu} = \frac{1}{2}\int d^3x\, \vec{x} \times \vec{J}(\vec{x})$$

$$\vec{a} = \int d^3x\, x^2\, \vec{J}(\vec{x})$$

EDMs: Exploiting Nuclear Structure

VOLUME 51, NUMBER 21 PHYSICAL REVIEW LETTERS 21 NOVEMBER 1983

Enhanced *T*-Nonconserving Nuclear Moments

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(Received 8 August 1983)

T- and *P*-nonconserving nuclear moments induced by a parity- and *CP*-nonconserving interaction in the QCD Lagrangian are discussed. The mixing of nearly degenerate opposite-parity ground-state doublets in certain deformed nuclei leads to electric dipole and magnetic quadrupole moments 10^1–10^3 and 10^3–10^4 times larger, respectively, than those generated by the unpaired valence nucleon.

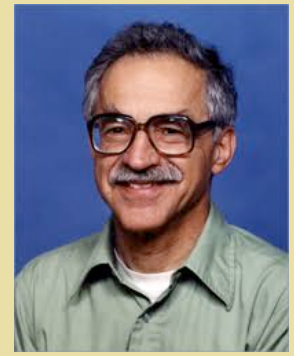
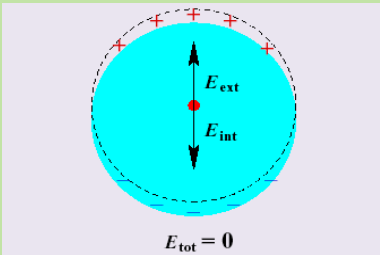


TABLE I. Nuclear electric dipole and magnetic quadrupole moments.

Nucleus	$[Nn_Z\Lambda, K^\pi]_{g.s.}$ [a]	$[Nn_Z\Lambda, K^\pi]_{e.s.}$ [a]	ΔE (keV)	$\langle 1\|V\|0\rangle/\bar{g}$ (keV) [b]	$\langle 0\|\|GT\|\|0\rangle$ [b]	$\langle 0\|\|E1\|\|1\rangle$ [c]	D_N/d_n	$M2/m2$
^{153}Sm	$[651, \frac{3}{2}^+]$	$[521, \frac{3}{2}^-]$	35.8	−170	−0.65	>3.74	>86.1	>10.1
^{161}Dy	$[642, \frac{5}{2}^+]$	$[523, \frac{5}{2}^-]$	25.7	−237	−1.21	0.39	10.3	−541
^{165}Er	$[523, \frac{5}{2}^-]$	$[642, \frac{5}{2}^+]$	47.2	213	1.03	0.64	9.6	664
^{225}Ac	$[532, \frac{3}{2}^-]$	$[651, \frac{3}{2}^+]$	40.0	180	−0.56	<−0.74	>19.3	<−610
^{227}Ac	$[532, \frac{3}{2}^-]$	$[651, \frac{3}{2}^+]$	27.4	187	−0.56	−0.21	8.7	−926
^{229}Pa	$[642, \frac{5}{2}^+]$	$[523, \frac{5}{2}^-]$	0.22	39	1.05	−4.58	2390	12400

Schiff Theorem

Schiff Screening



Classical picture: non-acceleration of neutral non-rel system

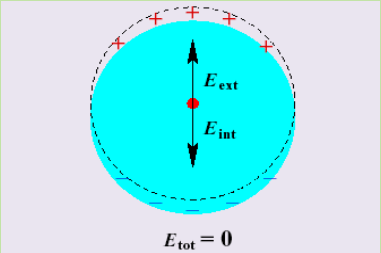
The EDM of a neutral system will vanish if:

- *Constituents are non-relativistic*
- *Constituents are point-like*
- *Interactions are electrostatic*

Diamagnetic atoms w/ large A: nuclei are large $r \sim (1\ \mathrm{fm}) \times A^{1/3}$

Nuclear Schiff Moment

Schiff Screening



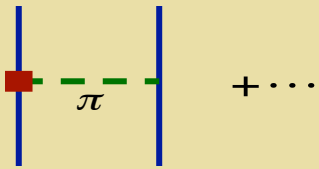
Atomic effect from nuclear finite size: Schiff moment

Nuclear Schiff Moment

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

Nuclear EDM: Screened in atoms

$$d_{\mathrm{nuc}} \sim \int d^3x\, \vec{x}\, \rho(\vec{x})^{\mathrm{CPV}}$$



EDMs of diamagnetic atoms (^{199}Hg)

Nuclear Schiff Moment

PHYSICAL REVIEW C **76**, 035503 (2007)

Atomic electric dipole moments: The Schiff theorem and its corrections

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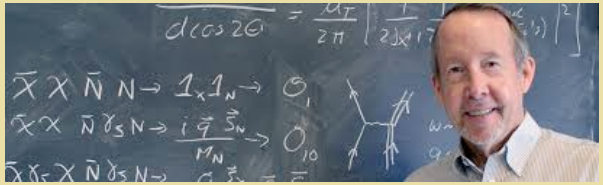
(Received 14 May 2007; published 24 September 2007)

A career-long research problem



Summary

- ***Pioneer in fundamental symmetry tests in general & PV in nuclei in particular***
- ***Example of insatiable drive to understand laws of nature***
- ***Inspiration to many***

Thanks Wick !