PNC in Atoms and Electron EDM

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September 16, 2002

Abstract

Measurements and calculations of parity nonconservation (PNC) in atoms are reviewed with emphasis on the $6s \rightarrow 7s$ transition in cesium and the corresponding value of the weak charge $Q_W(^{133}\text{Cs})$. An experiment in thallium, designed to detect an atomic electric dipole moment (EDM), which signals violation of time-reversal symmetry, is discussed along with the corresponding limit on the electron EDM.

Highlights for PNC in ^{133}Cs

- Precise (0.35%) measurement of E_{PNC}/β.[1]
- Re-measurement of β.[2]
- Re-analysis of accuracy of structure calculations.[3]
- Conclusion: 2.5 σ difference of Q_W^{exp} with standard model.[3]
- Led to speculation concerning physics beyond the SM, including: new Z' particles, scalar leptoquarks, four-fermion contact interactions ...
- Led to a re-analysis of small (Breit, QED, "skin") corrections.

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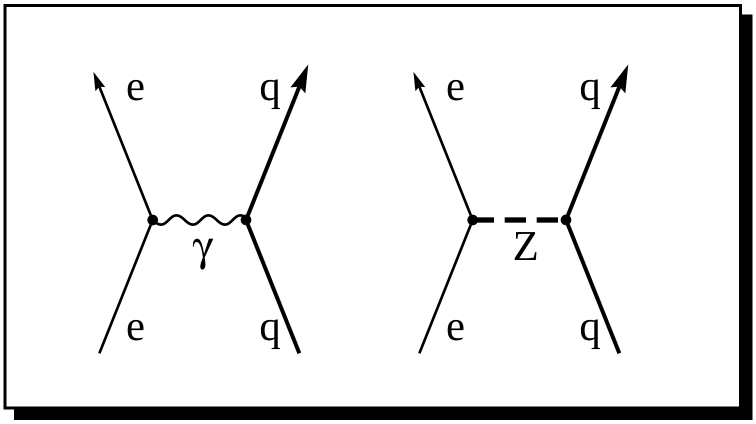
[1] C. S. Wood et al., Science **275**, 1759 (1997).
[2] S. C. Bennett and C. E. Wieman, Phys. Rev. Lett. **82**, 4153 (1999).
[3] D. E. Groom et al., Euro. Phys. J. C **15**, 1 (2000).

Review



Consequence: Laporte's rule[4] is violated!

$$|jl\rangle \rightarrow |jl\rangle + \epsilon\,|jl \pm 1\rangle$$

[4]O. Laporte, Z. Physik **23** 135 (1924).

Background

Standard electroweak model[5]

$$H_{\mathsf{PV}} = \frac{G}{\sqrt{2}} \Big[\bar{e}\gamma_\mu\gamma_5 e \left(c_{1u}\, \bar{u}\gamma_\mu u + c_{1d}\, \bar{d}\gamma_\mu d + \cdots \right) + \bar{e}\gamma_\mu e \left(c_{2u}\, \bar{u}\gamma_\mu\gamma_5 u + c_{2d}\, \bar{d}\gamma_\mu\gamma_5 d + \cdots \right) \Big]$$

where $\cdots$ corresponds to $q = s, t, b, c$.

$$c_{1u} = -\frac{1}{2} + \frac{4}{3}\sin^2\theta_W$$

$$c_{1d} = \frac{1}{2} - \frac{2}{3}\sin^2\theta_W$$

$$c_{2u} = -1/2\left(1 - 4\sin^2\theta_W\right)$$

$$c_{2d} = 1/2\left(1 - 4\sin^2\theta_W\right)$$

[5] W. J. Marciano in *Precision Tests of the Standard Electroweak Model*, Ed. P. Langacker, (World Scientific, Singapore, 1995), p. 170

Contribution of $A_e V_q$

We can extract an "effective" Hamiltonian to be used in the electron sector

$$\boxed{H^{(1)} = \frac{G}{2\sqrt{2}}\,\gamma_5\, Q_W\, \rho(r)}$$

where $\rho(r)$ is a nuclear density ($\sim$ neutron density) normalized to 1, and (omitting radiative corrections)

$$\begin{aligned} Q_W &= 2[(2Z+N)c_{1u} + (Z+2N)c_{1d}] \\ &= -N + Z\,(1 - 4\,\sin^2\theta_W) \end{aligned}$$

- $H^{(1)}$ is the dominant PNC interaction.
- Q_W is a conserved charge (the neutral weak vector current is conserved).

Nuclear Spin Dependent Terms

The $V_e A_q$ interaction leads to:

$$H^{(2)} = -\frac{G}{\sqrt{2}} \boldsymbol{\alpha}\cdot \left[c_{2p} \left\langle \phi_p^\dagger \boldsymbol{\sigma} \phi_p \right\rangle + c_{2n} \left\langle \phi_n^\dagger \boldsymbol{\sigma} \phi_n \right\rangle \right]$$

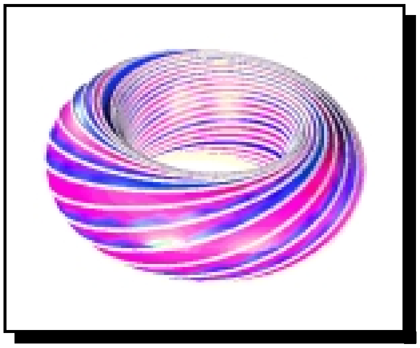
$$= \eta^{(2)} \frac{G}{\sqrt{2}} \boldsymbol{\alpha} \cdot \boldsymbol{I} \; \rho_n(r)$$

Values of $\eta^{(2)}$ in the extreme nuclear shell model.

Element	A	type	nuc state	$\eta^{(2)}$
Cs	133	p	$1g_{7/2}$	0.0105
Ba	135	n	$2d_{3/2}$	0.0189
Tl	205	p	$3s_{1/2}$	-0.0944
Fr	209	p	$1h_{9/2}$	0.00858
K	39	p	$1d_{3/2}$	0.0189

Other Spin-Dependent Terms

(a) Nuclear anapole moment[6]



$$H^{(a)} = \eta^{(\mathrm{a})} \frac{G}{\sqrt{2}} \alpha \cdot \mathbf{I} \, \rho_n(r)$$

(b) $H_{\mathrm{hf}} \times H^{(1)}$ interference[7]

$$H^{(\mathrm{int})} = \eta^{(\mathrm{int})} \frac{G}{\sqrt{2}} \alpha \cdot \mathbf{I} \, \rho_n(r)$$

[6] Ya. B. Zeldovich, Sov. Phys. JETP **9**, 682 (1959).

[7] C. Bouchiat and C. A. Piketty, Z. Phys. C 49, 91 (1991); Phys. Lett. B 269, 195 (1991).

Experiments

An electric-dipole transition matrix element between states of the same nominal parity is measured. In cesium, for example, the matrix element

$$E_{\mathsf{PNC}} = \langle 7s|ez|6s\rangle \propto Q_W \times \text{“Structure Factor”}$$

is measured.

- Optical Rotation: $n_- \neq n_+$

$$\boxed{R_\phi = \mathrm{Im}\left(E_{\mathsf{PNC}}\right)/M1}$$

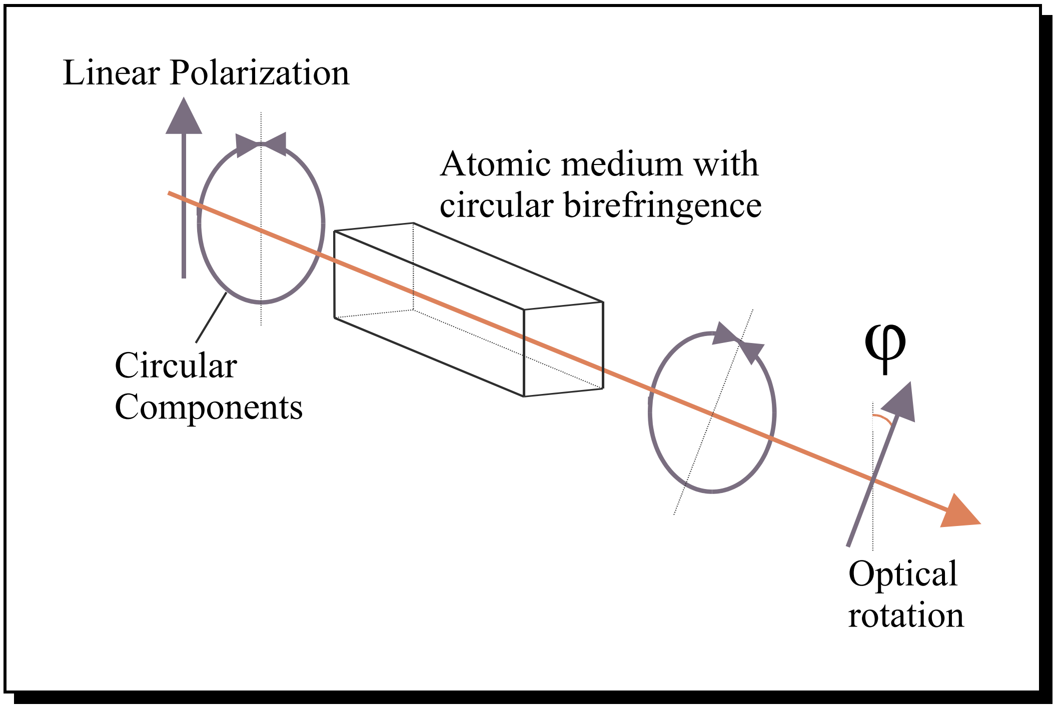
  where M1 is the magnetic-dipole transition matrix element.

- Interference with a Stark-induced PV matrix element:

$$\boxed{R_{\mathsf{Stark}} = \mathrm{Im}\left(E_{\mathsf{PNC}}\right)/\beta}$$

  where β is the vector polarizability of the transition.

Schematic of O.R. Experiment



The plane of polarization of a linearly polarized laser beam passing through a medium with $n_+ \neq n_-$ is rotated. The rotation angle $\phi \propto R_\phi = \mathrm{Im}\left(E_{\mathsf{PNC}}\right)/M1$.

Optical Rotation Experiments

$$R_\phi = \text{Im}\left(E_{\text{PNC}}\right)/M1$$

Measured values of R_ϕ

Element	Transition	Group	$10^8 \times R_\phi$
^{205}Tl	$^2P_{1/2} - {}^2P_{3/2}$	Oxford (95)	-15.33(45)
^{205}Tl	$^2P_{1/2} - {}^2P_{3/2}$	Seattle (95)	-14.68(20)
^{208}Pb	$^3P_0 - {}^3P_1$	Oxford (94)	-9.80(33)
^{208}Pb	$^3P_0 - {}^3P_1$	Seattle (95)	-9.86(12)
^{209}Bi	$^4S_{3/2} - {}^2D_{3/2}$	Oxford (91)	-10.12(20)

Analysis for ^{205}Tl

The difference between the Oxford and Seattle values in the table was resolved by Majumder and Tsai[8]

$$R_\phi(^{205}\mathsf{Tl}) = -14.71(25).$$

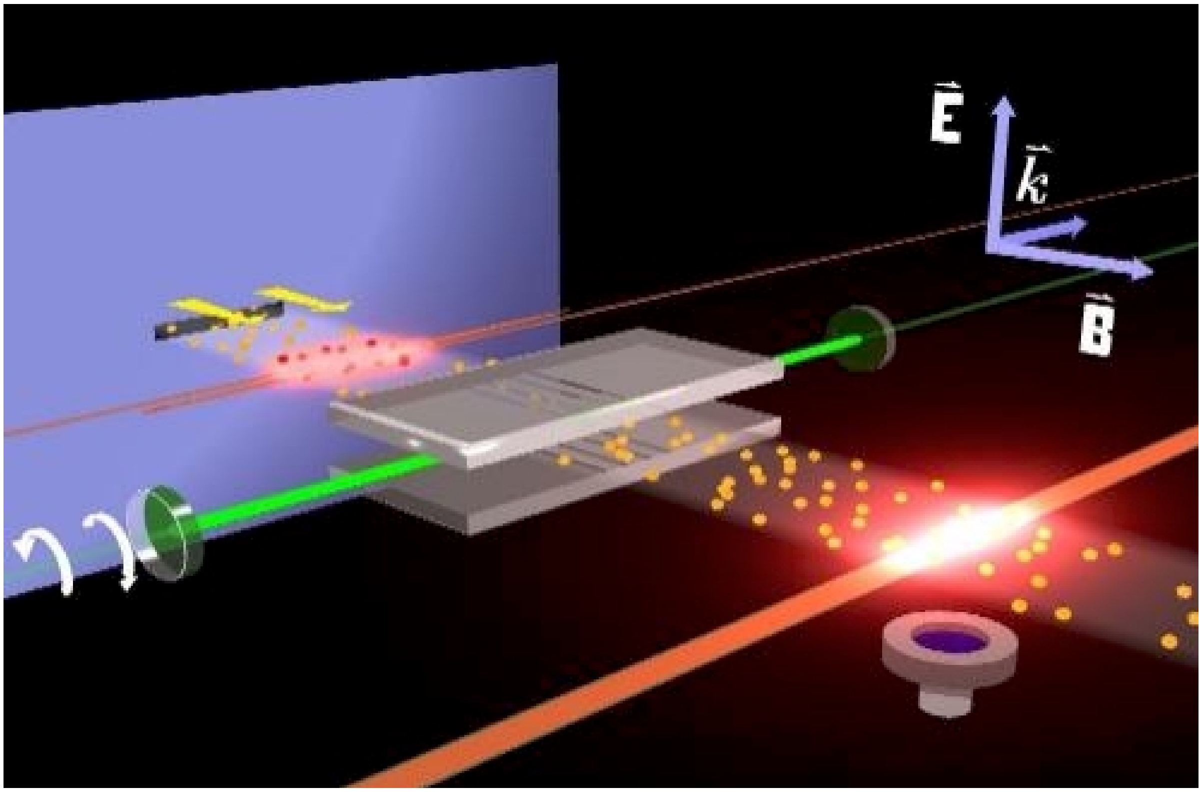
Using a recent structure calculation[9] (3% error)

$$Q_W^{\mathsf{exp}}(^{205}\mathsf{Tl}) = -\,113(3)$$
$$Q_W^{\mathsf{SM}}(^{205}\mathsf{Tl}) = -\,116(1)$$

Better calculations for Tl needed!

8 P. K. Majumder and L. L. Tsai, Phys. Rev. A **60**, 267 (1999).
9 M. G. Kozlov et al., Phys. Rev. A **64**, 052107 (2001).

Schematic of Stark-Interference Experiment



Schematic of the Boulder PNC apparatus. A beam of cesium atoms is optically pumped by diode laser beams, then passes through a region of perpendicular electric and magnetic fields where a green laser excites the transition from the 6S to the 7S state. Finally the excitations are detected by observing the florescence (induced by another laser beam) with a photodiode.

Stark-Induced Transition Experiments

Evolving values of $R = \text{Im}\,(E_{\text{PNC}})\,/\beta$ (mV/cm) for ^{133}Cs			
Transition	Group	R_{4-3}	R_{3-4}
$6s_{1/2} - 7s_{1/2}$	Paris (1984)	-1.5(2)	-1.5(2)
$6s_{1/2} - 7s_{1/2}$	Boulder (1988)	-1.64(5)	-1.51(5)
$6s_{1/2} - 7s_{1/2}$	Boulder (1997)	-1.635(8)	-1.558(8)

The vector current contribution from the last row is

$$R_{\text{Stark}} = -1.593 \pm 0.006$$

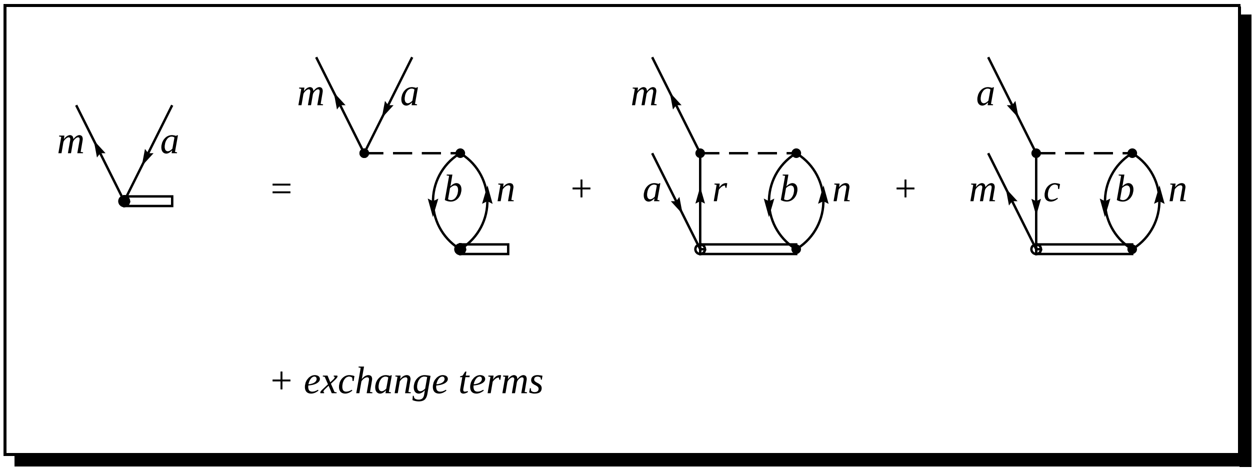
$$\text{Im}\left[E_{\text{PNC}}(6s \to 7s) \times 10^{11}\right] = -0.8374 \pm (0.0031)_{\text{exp}} \pm (0.0021)_{\text{th}}$$

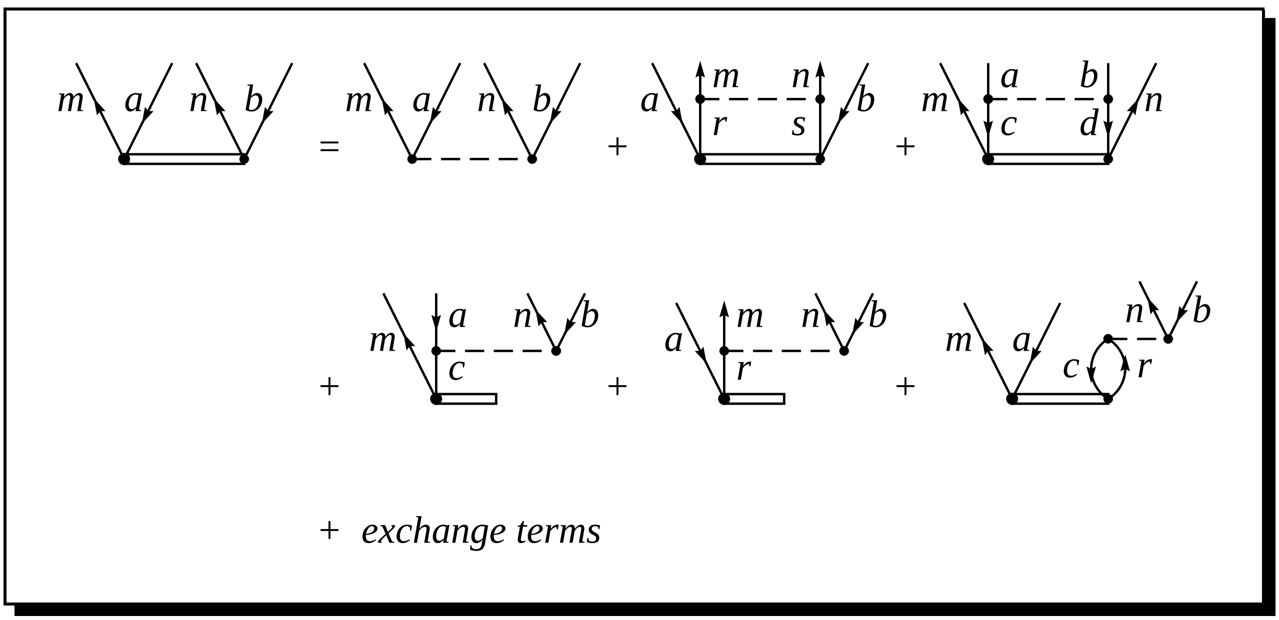
Calculations of the $6s \rightarrow 7s$ amplitude

The most recent many-body calculation[10] uses a method referred to as "perturbation theory in the screened Coulomb interaction" (PTSCI) in which important classes of many-body diagrams are summed to all orders. This gives results consistent with the SD Coupled-Cluster (SDCC) calculations.[11]

[10] V. A. Dzuba et al., arXiv:hep-ph/0204134 (2002).
[11] S. A. Blundell et al., Phys. Rev. D**45**, 1602 (1992).

Brueckner-Goldstone Diagrams for the SDCC Equations





Breakdown of Dominant Contribution: ^{133}Cs

n	$\langle 7s\|ez\|np\rangle$	$\langle np\|H^{(1)}\|6s\rangle$	$E_{6s} - E_{np}$	Term
6	1.7291	-0.0562	-0.05093	1.908
7	4.2003	0.0319	-0.09917	-1.352
8	0.3815	0.0215	-0.11714	-0.070
9	0.1532	0.0162	-0.12592	-0.020
n	$\langle 7s\|H^{(1)}\|np\rangle$	$\langle np\|ez\|6s\rangle$	$E_{7s} - E_{np}$	Term
6	-1.8411	0.0272	0.03352	-1.493
7	0.1143	-0.0154	-0.01472	0.120
8	0.0319	-0.0104	-0.03269	0.010
9	0.0171	-0.0078	-0.04147	0.003
Total				-0.893

Units: $i(-Q_W/N) \times 10^{-11}$

Residuals

$\sum_{n=6}^{9}$	All-Order	-0.893(3)
$\sum_{n=10}^{\infty}$	RPA	-0.018(2)
Autoionizing	HF	0.002(2)
Total		-0.909(4)

n.b. Most recent PTSCI value -0.908(5)

Units of $H^{(1)}$: $i(-Q_W/N) \times 10^{-11}$

Analysis of $6s \to 7s$ amplitude in ^{133}Cs

Combining the calculations and the measurements, we find

$$Q_W^{\text{exp}}(^{133}\text{Cs}) = -71.90(48),$$

As mentioned previously, this disagrees by 2.5 σ with the standard model value[4]

$$Q_W^{\text{SM}}(^{133}\text{Cs}) = -73.09(3).$$

What's Missing?

(A) Breit Interaction[12]

Type	$\langle 7s\|ez+\delta V_z^{\mathsf{HF}}\|\widetilde{6s}\rangle$	$\langle\widetilde{7s}\|ez+\delta V_z^{\mathsf{HF}}\|6s\rangle$	E_{PNC}
Coul	0.43942	-1.33397	-0.89456
+ Breit	0.43680	-1.32609	-0.88929
Δ%	-0.60%	-0.59%	-0.59%

[12]A. Derevianko, Phys. Rev. Lett. **85**, 1618 (2000).

Another Missing Piece

(B) Vacuum-Polarization[13]

RPA-level calculations

Type	$\langle 7s \vert ez + \delta V_z^{\mathsf{HF}} \vert \widetilde{6s} \rangle$	$\langle \widetilde{7s} \vert ez + \delta V_z^{\mathsf{HF}} \vert 6s \rangle$	E_{PNC}
Coul	0.3457	-1.2726	-0.9269
+ V.P.	0.3471	-1.2778	-0.9307
Δ%	0.41%	0.41%	0.41%

[13]W. R. Johnson, I. Bednyakov, and G. Soff, Phys. Rev. Lett. **87**, 233001 (2001); A. I. Milstein and O. P. Sushkov, arXiv:hep-ph/0109257

Vertex Correction

In vacuum the scale factor for Q_W is:[14]

$$1 - \frac{\alpha}{2\pi} + \frac{\alpha(m_Z)}{2\pi}\left\{ \frac{3}{8s^2}\frac{m_t^2}{m_W^2} + \frac{3}{8s^4}\ln c^2 - \frac{7}{8s^2} + \frac{3\xi}{8s^2}\left(\frac{\ln(c^2/\xi)}{c^2-\xi} + \frac{1}{c^2}\frac{\ln\xi}{1-\xi}\right) - \frac{1}{s^2} + \cdots \right\}$$

In a nuclear Coulomb field, the vertex correction

$$-\frac{\alpha}{2\pi} \to \mathcal{V}$$

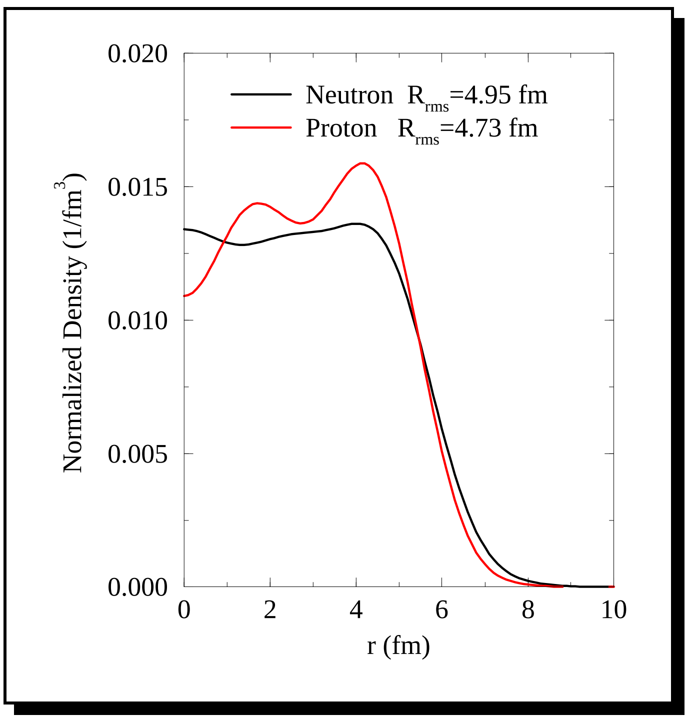
Group	$\mathcal{V}$
Milstein & Sushkov (2001)	-0.1
Kuchiev & Flambaum (2002)	-0.73
Milstein, Sushkov & Terekhov (2002)	-0.85
Kuchiev (2002)	-0.90

[14] W. J. Marciano in *Precision Tests of the Standard Electroweak Model*, Ed. P. Langacker, (World Scientific, Singapore, 1995), p. 182

Nuclear "skin" correction

Neutrons are primarily the source of the vector atomic PNC interaction, but proton densities are used in calculations of atomic PNC.

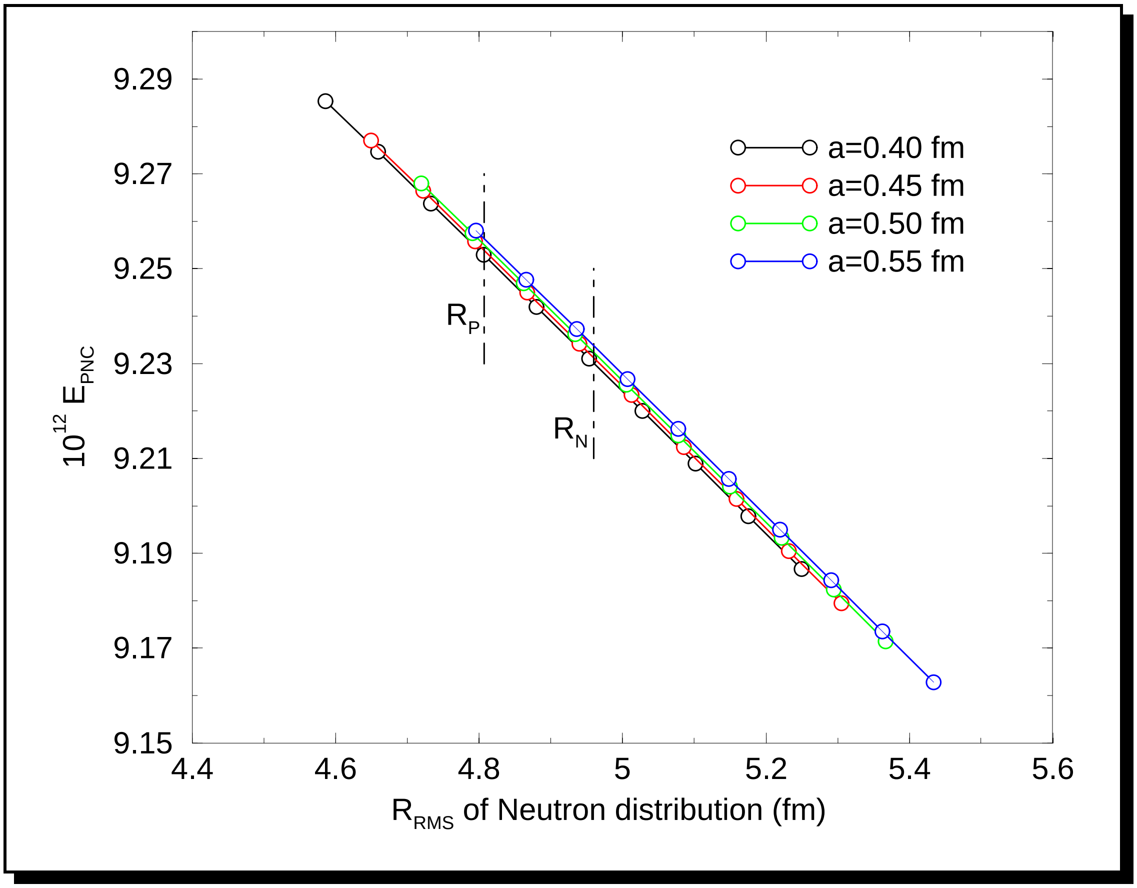
Replacing proton densities by neutron densities leads to "skin" corrections proportional to $\delta\rho = \rho_n - \rho_p$.



Proton and Neutron distributions[15] for ^{133}Cs.

[15] D. Vretenar et al., Phys. Rev. C **62**, 045502 (2000).

RPA Calculations



Conclusion:[16,17,18] The "skin" effect decreases the size of E_{PNC} by 0.1% -0.2%

[16] A. Derevianko, Phys. Rev. A**65**, 052115 (2001)
[17] S. J. Pollock and M. C. Welliver, Phys. Lett. B **464**, 177 (1999)
[18] J. James and P. G. H. Sandars, J. Phys. B**32**, 3295 (1999)

Conclusion (for ^{133}Cs)

Including the (Br+VP+Vertex+"skin") corrections changes theory value to

$$E_{\rm PNC} = -0.8981 \ \pm 0.0037 \ iea_0 \times 10^{-11}(-Q_W/N)$$

Combining this with the experimental value of $E_{\rm PNC}/\beta$, leads to an experimental value for the weak charge

$$Q_W^{\rm expt}(^{133}{\rm Cs}) = -72.73 \pm (0.26)_{\rm expt} \pm (0.34)_{\rm theor}$$

- Without "vertex" differs by $2.2\ \sigma$ from SM
- With "vertex" differs by 0.8 σ from SM

Francium (Z=87)

- $E_{\text{PNC}}(\text{Fr})[7s_{1/2} \to 8s_{1/2}] \sim 15 \times E_{\text{PNC}}(\text{Cs})$
- $^{208-221}$Fr produced and trapped at SUNYSB[19]
- $T_{1/2} \sim 20$m for some isotopes (^{212}Fr)
- Spectrum established[20]
- Precision measurement of lifetimes and hyperfine constants[21]
- A microwave cavity experiment to measure the I-dependent PNC between ground-state hyperfine levels in Fr isotopes is underway.[22]

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[19] J. E. Simsarian et al., Phys. Rev. Lett. **76**, 3522 (1996).
[20] J. E. Simsarian et al., Opt. Lett. **21**, 1939 (1996).
[21] J. S. Grossman et al., Physica Scripta T**86**, 16 (2000).
[22] S. Aubin et al., Proceedings of International Conference on Laser Spectroscopy, 2001.b

Ba$^+$ ion (Z=56)

A experiment is underway in Seattle to measure PNC in a single trapped barium ion.[23]

- Transition: $6s_{1/2} \to 5d_{3/2}$
- $E_{\text{PNC}} \sim 10^{-11} e\, a_0$ - competitive with Cs
- Seven naturally occurring isotopes, ∴ possibility of eliminating computational uncertainties by comparing results from different isotopes
- Two odd A isotopes ^{135}Ba and ^{137}Ba (I=3/2) can give information about I-dependent PNC terms (from an unpaired neutron)
- Recent progress[24] has been made on the spectroscopy of Ba$^+$

[23] N. Fortson, Phys. Rev. Lett. **70**, 2383 (1993).
[24] T. W. Koerber et al., Phys. Rev. Lett. **88**, 143002 (2002).

Ytterbium (Z=70)

- Seven naturally occurring isotopes $^{168-176}$Yb
- Two odd A isotopes ^{171}Yb (1/2) and ^{173}Yb (5/2)
- $E_{\mathsf{PNC}}(\mathsf{Yb})[^1S_0 \rightarrow ^3 D_1] \sim 100 \times E_{\mathsf{PNC}}(\mathsf{Cs})$ [25]
- Mixing of $(6s5d)^3D_1$ with nearby $(6s6p)^1P_1$
- Only I-dependent terms $\Rightarrow E_{\mathsf{PNC}}(\mathsf{Yb})[^1S_0 \rightarrow ^3 D_2]$
- Spectroscopy ($E2$, $M1$, β) of Yb studied[26,27]
- Progress and details given at Berkeley website [28]

[25] D. DeMille, Phys. Rev. Lett. **74**, 4165 (1995).
[26] C. J. Bowers et al., Phys. Rev. A **59**, 3513 (1999).
[27] J. E. Stalnaker et al., Phys. Rev. A **65**, (2002).
[28] ist-socrates.berkeley.edu/budker/

Dysprosium (Z=66)

Atomic dysprosium has two nearly degenerate levels of opposite parity $a = (4f^{10}5d6s)[10]$ and $b = (4f^{9}5d^{2}6s)[10]$ at 19797.96 cm^{-1} above the ground state.

- Seven naturally occurring isotopes — comparisons
- Two odd A isotopes ^{161}Dy and ^{163}Dy (I=5/2) - information about I-dependent PNC terms
- A Stark interference experiment[29] to detect the PNC mixing between a and b gave $|H_W| = |2.3 \pm 2.9 \pm 0.7|$ Hz,
- A multi-configuration Dirac-Fock calculation[30] gave $H_W = 70(40)$ Hz — correlation dependent matrix element!

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[29] A.-T. Nguyen et al., Phys. Rev. A **56**, 3453 (1997).
[30] V. A. Dzuba et al., Phys. Rev. A **50**, 3812 (1994).

Samarium (Z=62)

The optical rotation parameter $R\phi$ was measured[31] for five $M1$ transitions in the ground-state multiplet of atomic samarium.

- Lower state: $(4f^6 6s^2)\ ^7F$
- Upper state: $(4f^6 6s^2)\ ^5D$
- The upper state levels are nearly degenerate with levels of opposite parity from the $(4f^6 6s 6p)$ configuration. (expect enhancement)
- $|H_W| =$ 1–30 kHz for the 5 levels.
- Result is 1 - 2 orders of magnitude smaller than expected from semi-empirical calculations!

[31] D. M. Lucas et al., Phys. Rev. A **58**, 3457 (1998).

Results on anapole moment

$$\eta_{\mathsf{exp}}(^{133}\mathsf{Cs}) = 0.112(16)$$

$$\eta_{\mathsf{exp}}(^{205}\mathsf{Tl}) = 0.29(40)$$

The axial current term gives

$$\eta^{(2)}(^{133}\mathsf{Cs}) = 0.0140$$

$$\eta^{(2)}(^{205}\mathsf{Tl}) = -0.127$$

The interference term gives[32]

$$\eta^{(\mathsf{int})}(^{133}\mathsf{Cs}) = 0.0078$$

$$\eta^{(\mathsf{int})}(^{205}\mathsf{Tl}) = 0.044$$

Residual anapole contribution[33]

$$\eta^{(a)}(^{133}\mathsf{Cs}) = 0.090(16)$$

$$\eta^{(a)}(^{205}\mathsf{Tl}) = 0.38(40)$$

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[32] C. Bouchiat and C. A. Piketty, Z. Phys. C 49, 91 (1991); Phys. Lett. B 269, 195 (1991).

[33] W. C. Haxton and C. E. Wieman, Ann. Rev. Nucl. Part. Sci. **51**, 261 (2001).

Conclusions for Anapole Moment

1. Measured anapole moments are inconsistent with most general theory constraints on nuclear weak coupling constants.

2. Nuclear theory favors a negative anapole moment for Tl; experiment gives a positive value (or zero).

3. Nuclear theory predicts a value for Cs larger than observed.

What would be useful?

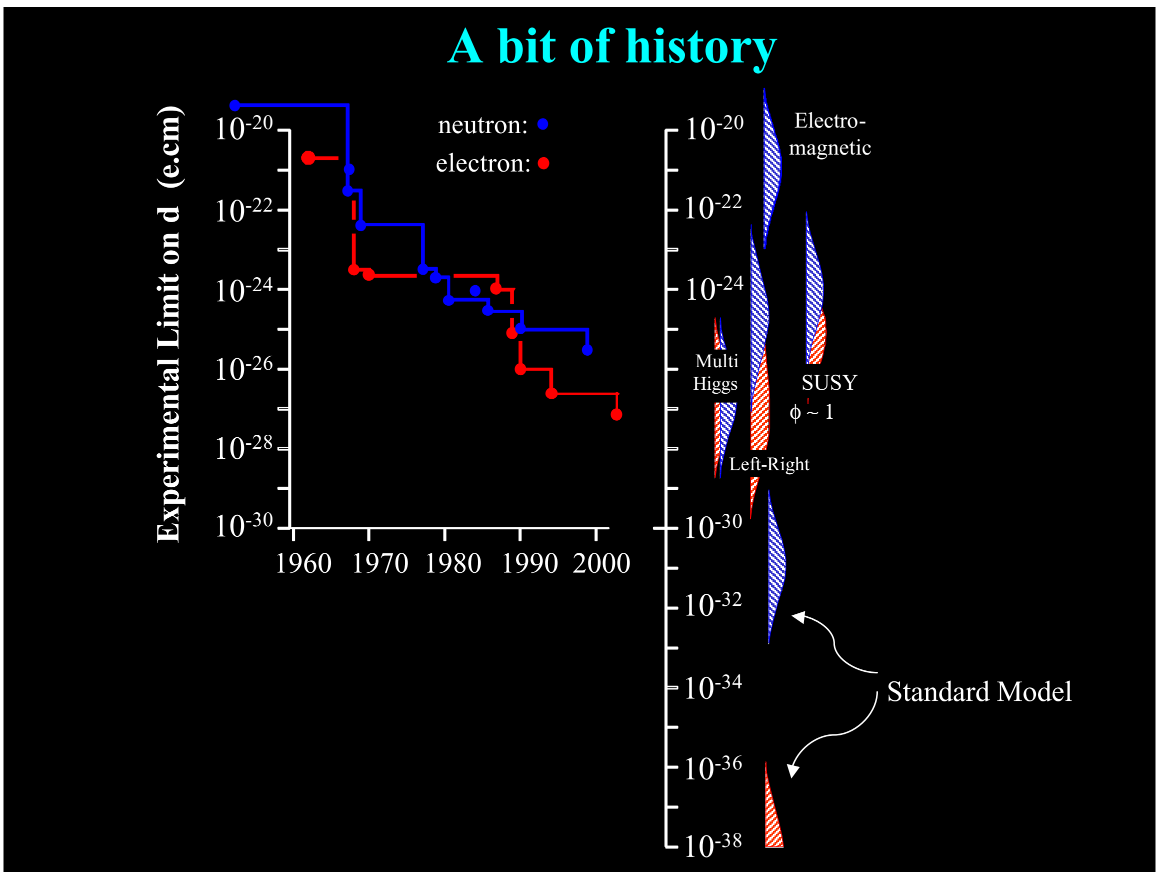
1. Improved thallium measurement

2. Moments from other nuclei (Fr, Yb, Ba^+)

Electron EDM and T violation

The P-odd T-odd interaction of an intrinsic electron EDM d with an $\boldsymbol{E}$ field is

$$H_{\mathrm{edm}} = -d\,\beta\,\boldsymbol{\sigma}\cdot\boldsymbol{E}.$$



Atomic EDM I

To measure d, examine an electron in a neutral atom.

The many-electron Hamiltonian for an atom becomes

$$H = H_0 + \frac{d}{e} \sum_i \beta_i \, \boldsymbol{\sigma}_i \boldsymbol{\cdot} \boldsymbol{\nabla}_i V$$
$$- \sum_i \left[e \, \boldsymbol{r}_i + d \, \beta_i \, \boldsymbol{\sigma}_i \right] \boldsymbol{\cdot} \boldsymbol{E} \, .$$

where

$$V = \sum_i V_{\mathsf{nuc}}(i) + \frac{1}{2} \sum_{ij} \frac{e^2}{r_{ij}}$$

Atomic EDM II

For an external electric field of strength E in the z direction, the atom-field interaction energy of an atom in a state v with projection m_v is

$$W_{m_v} = -\langle v m_v | \sum_i \left[e\, z_i + d\, \beta_i\, \sigma_{3i} \right] | v m_v \rangle E = -\frac{m_v}{j_v} D E$$

This equation serves to define the atomic dipole moment D. Thus

$$D = \langle v j_v | \sum_i \left[e\, z_i + d\, \beta_i\, \sigma_{3i} \right] | v j_v \rangle .$$

To order d in perturbation theory, $D = D^{(0)} + D^{(1)}$

$$D^{(0)} = d\, \langle v j_v | \sum_i \beta_i\, \sigma_{3i}\, | v j_v \rangle$$

$$D^{(1)} = d \sum_n \frac{\langle v j_v | \sum_i z_i\ | n \rangle\ \langle n | \sum_i \beta_i \boldsymbol{\sigma}_i \cdot \boldsymbol{\nabla}_i V\ | v j_v \rangle}{E_v - E_n}$$

$$+\ d \sum_n \frac{\langle v j_v | \sum_i \beta_i \boldsymbol{\sigma}_i \cdot \boldsymbol{\nabla}_i V\ | n \rangle\ \langle n | \sum_i z_i\ | v j_v \rangle}{E_v - E_n} .$$

Schiff's Theorem

Replace β by I in expression for D to find

$$D^{(0)} + D^{(1)} = 0$$

Thus, in the nonrelativistic limit, $D = 0$.

With this in mind, the calculation can be reduced to the evaluation of

$$D = 2 \sum_n \frac{\langle v j_v | Z | n \rangle \ \langle n | H_{\text{edm}} \ | v j_v \rangle}{E_v - E_n},$$

with the effective (one-particle) edm Hamiltonian

$$H_{\text{edm}} = -2id\,c \sum_j p_j^2 \, \beta_j \, (\gamma_5)_j = H_{\text{edm}}^\dagger \, .$$

and

$$Z = \sum_i z_i$$

Calculations

Dirac-Hartree-Fock Results			
Atom	G.S.	Z	D/d
Li	$2s$	3	0.00294
Na	$3s$	11	0.240
K	$4s$	19	1.99
Rb	$5s$	37	19.5
Cs	$6s$	55	94.0
Au	$6s$	79	327.5
Tl	$6p$	81	-419.5

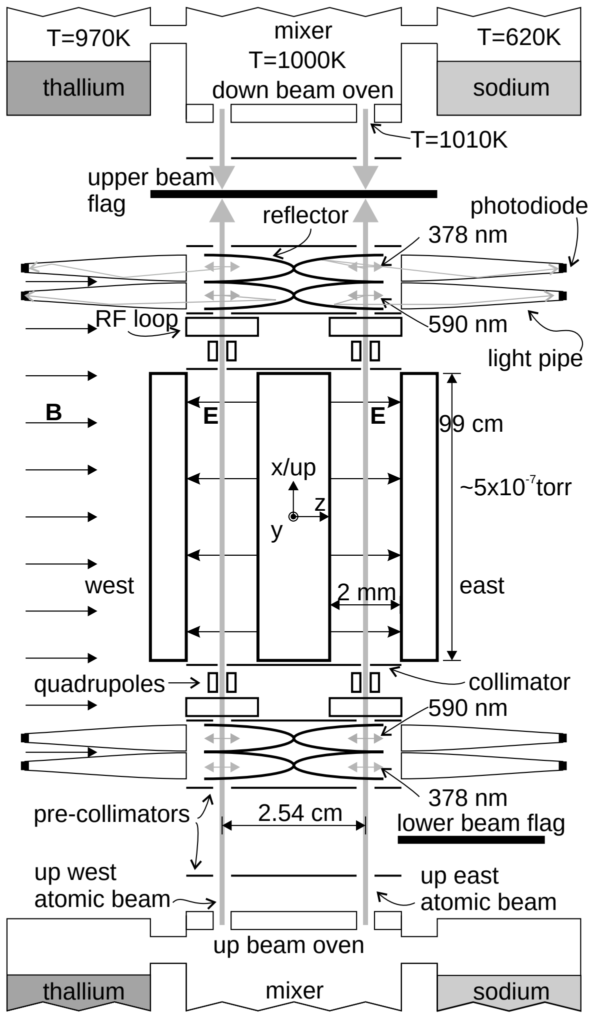
Best available result for Tl:

$$\frac{D}{d} = -585 \pm 30$$

from a SDCC calculation.[34]

[34] Z.-W. Liu and H. Kelly, Phys. Rev. A **45**, R4210 (1992).

Tl Experiment[35]



$$|d_e| \leq 1.6 \times 10^{-27}\ e\ \text{cm}$$

[35] B. C. Regan et al., Phys. Rev. Lett. **88**, 071805 (2002)

Gas Phase EDM Experiments

- PbO (D. deMille,[36] Yale)
- YbF (E. Hinds,[37] Sussex)
- TlF (V. Ezhov,[38] Gatchina)

[36] L. R. Hunter et al. Phys. Rev. A**65**, 030501 (2002)
[37] J. J. Hudson et al., Phys. Rev. Lett. **89**, 013003 (2002)
[38] A. N. Petrov et al., Phys. Rev. Lett. **88**, 073001 (2002)

New Electron EDM Experiment[39]

- Garnet magnet: $Gd_3Fe_5O_{12}$ or $Gd_3Ga_5O_{12}$
- Active sites: Gd^{+3} $[Xe](4f)^7$ $^7S_{7/2}$
- Density: 10^{22} sites/cc
- Symmetry: FCC (eliminates systematics)
- $D/d \approx 2$ very uncertain because of f^7 configuration.
- Estimated limit $|d_e| = 10^{-29} - 10^{-31}$ e cm
- Construction underway at Amherst University[40]

[39] S. K. Lamoreaux, arXiv/nucl-ex/0109014
[40] L. Hunter //itamp.harvard.edu/fundamentalworkshop.html