# Status of Atomic PNC: Experiment/Theory

Walter Johnson
Department of Physics
Notre Dame University
http://www.nd.edu/∼johnson

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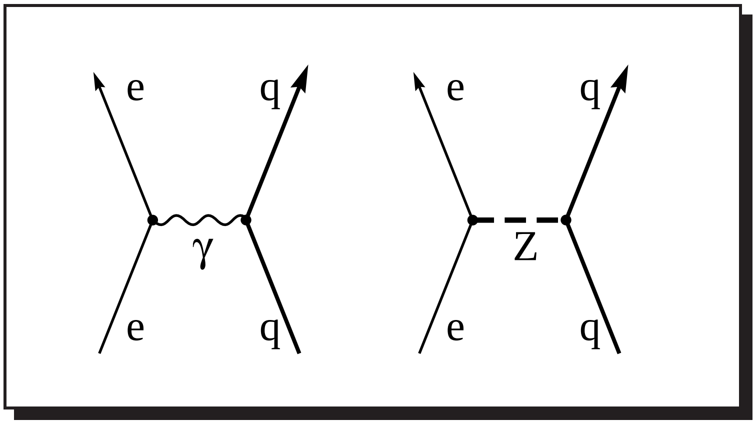
**Abstract**

Atomic PNC measurements and calculations are reviewed with emphasis on the $6s \rightarrow 7s$ transition in cesium and the corresponding value of the weak charge $Q_W(^{133}\mathrm{Cs})$.

# Reminder




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

$$Q_W = -N + Z\,(1 - 4\,s^2) \approx -N$$

Consequence: Laporte's rule[1] violated!

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

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

# Highlights for $6s \to 7s$ in $^{133}$Cs

- Precise (0.35%) measurement of $E_{\mathrm{PNC}}/\beta$.[2]

- Re-measurement of $\beta$.[3]

- Re-analysis of accuracy of structure calculations.[3]

- Conclusion: 2.5 $\sigma$ difference of $Q_W^{\mathrm{exp}}$ with standard model.[4]

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

# Optical Rotation Experiments

These experiments take advantage of the fact that $n_- \neq n_+$ and measure

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

where M1 is the magnetic-dipole transition matrix element.

Measured values of $R_\phi$

| 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[5]

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

Using a recent structure calculation[6] (3% error)

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

HELP! Better calculations for Tl needed.

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

# New and improved measurement in Tl

Cronin et al.[7] suggested that the optical rotation measurement of $R_\phi(6p_{1/2} \to 6p_{3/2})$ in thallium could be improved using the electromagnetically induced transparency[8] of a thallium vapor.

The method was used to obtain the ratio $E2/M1$ for the $6p_{1/2} \to 6p_{3/2}$ transition[7]

Details on Seattle group website.[9]

[7] A. D. Cronin et al., Phys. Rev. Lett. **80** 3719 (1998).
[8] K.-J. Boller et al., Phys. Rev. Lett. **66**. 2593 (1991).
[9] www.washington.edu/∼fortson

# Stark Interference

A laser excites an $E1$-forbidden transition in an atomic beam in a presence of electric $\boldsymbol{E}$ and magnetic $\boldsymbol{B}$ fields. The quantity measured is the component of the transition rate arising from the interference between $E_{\text{PNC}}$ and the Stark amplitude $\beta\boldsymbol{E}$ is then used to determine

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

This method has been used[10] to measure $R$ for the $6p_{1/2} \rightarrow 7p_{1/2}$ transition in $^{205}$Tl; the value of $\beta$ for this transition was also measured.[11]

The Stark interference method has also been used to study the $6s \rightarrow 7s$ transition in cesium.

[10] P. S. Drell and E. D. Commins, Phys. Rev. A **32**, 2196 (1985).
[11] C. E. Tanner and E. D. Commins, Phys. Rev. Lett. **56**, 332, (1986).

# The $6s \rightarrow 7s$ transition in $^{133}$Cs

| Values of $R_{\text{Stark}} = \text{Im}\left(E_{\text{PNC}}\right)/\beta$ (mV/cm) for cesium | | | | |
|---|---|---|---|---|
| Element | Transition | Group | $R_{4-3}$ | $R_{3-4}$ |
| $^{133}$Cs | $6s_{1/2} - 7s_{1/2}$ | Paris (1984) | -1.5(2) | -1.5(2) |
| $^{133}$Cs | $6s_{1/2} - 7s_{1/2}$ | Boulder (1988) | -1.64(5) | -1.51(5) |
| $^{133}$Cs | $6s_{1/2} - 7s_{1/2}$ | Boulder (1997) | -1.635(8) | -1.558(8) |

The vector current contribution from the last row is

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

Combining this with the value of $\beta$ from Ref.[3], leads to

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

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

The most recent many-body calculation[12] 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.[13] The calculated values are:

$$\begin{aligned} E_{\text{PNC}} = & 0.908(5), \qquad \text{(PTSCI)} \\ & 0.909(4), \qquad \text{(SDCC)} \end{aligned}$$

Units : $i(-Q_W/N)e\, a_0 \times 10^{-11}$

(We omit the Breit correction that was originally included in [12] and use the error estimate for that calculation given in Ref.[3].)

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

# 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 $\sigma$ with the standard model value[4]

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

# What's Missing?

(A) Breit Interaction[14]

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

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

# Another Missing Piece

(B) Vacuum-Polarization[15]

RPA-level calculations

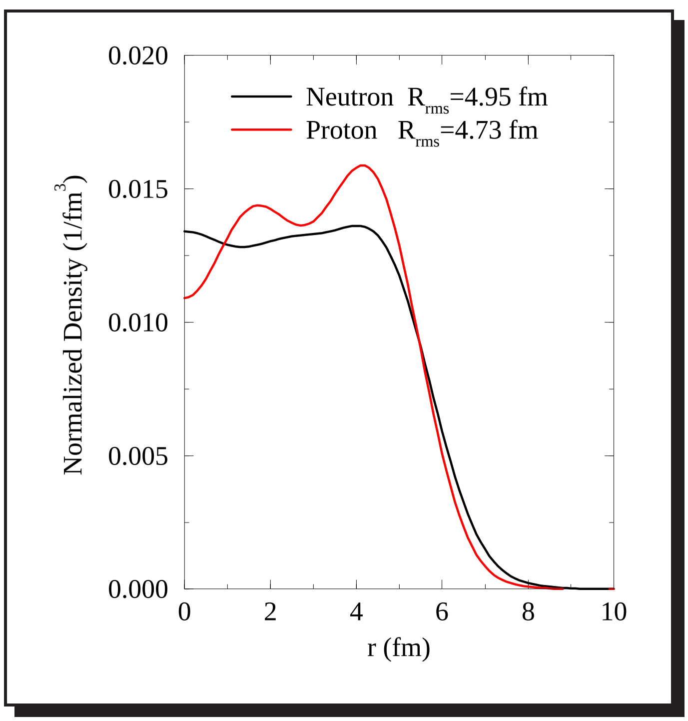
| Type | $\langle 7s \vert ez + \delta V_z^{\mathsf{HF}} \vert \widetilde{6s} \rangle$ | $\langle \widetilde{7s} \vert ez + \delta V_z^{\mathsf{HF}} \vert 6s \rangle$ | $E_{\mathsf{PNC}}$ |
|---|---|---|---|
| Coul | 0.3457 | -1.2726 | -0.9269 |
| Coul + V.P. | 0.3471 | -1.2778 | -0.9307 |
| $\Delta$%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

[15] 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

# Nuclear "skin" correction

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

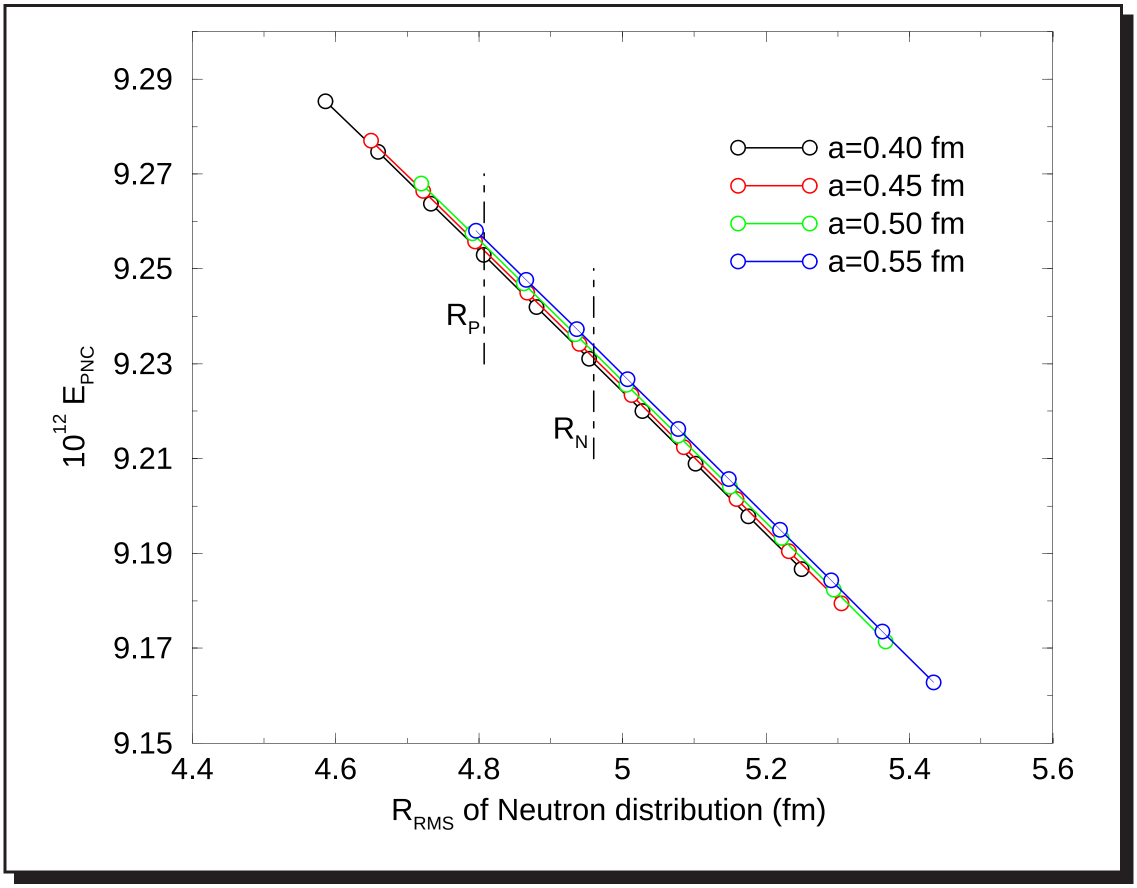
Replacing proton densities by neutron densities leads to "skin" corrections proportional to $\delta\rho = \rho_n - \rho_p$.




Proton and Neutron distributions[16] for $^{133}$Cs.

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

# RPA Calculations




Conclusion:[17,18,19] The "skin" effect decreases the size of $E_{\text{PNC}}$ by 0.1% -0.2%

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[17] A. Dervianko, arXiv:physics/0108033 (2001)

[18] S. J. Pollock and M. C. Welliver, Phys. Lett. B **464**, 177 (1999)

[19] J. James and P. G. H. Sandars, J. Phys. B**32**, 3295 (1999)

# Conclusion (for $^{133}$Cs)

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

$$\boxed{E_{\mathrm{PNC}} = -0.9053 \; \pm 0.0037 \; iea_0 \times 10^{-11}(-Q_W/N)}$$

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

$$\boxed{Q_W^{\mathrm{expt}}(^{133}\mathrm{Cs}) = -72.15 \pm (0.26)_{\mathrm{expt}} \pm (0.34)_{\mathrm{theor}}}$$

This still differs by 2.2 $\sigma$ from the standard-model value.

# Notes

⋆ The vertex QED correction is controversial!!

Milstein and Sushkov:[20] $\sim 0.1\%$

Kuchiev and Flambaum:[21] $-0.7\%$

⋆ The value of $\beta$ has been remeasured.[22]

$\beta = 27.22(11)\ a_0^3 \qquad \beta_{\mathrm{BW}} = 27.024(60)$

$\beta_{\mathrm{ave}} = 27.06(6)$

$Q_W \Rightarrow -72.25 \pm (0.26)_{\mathrm{expt}} \pm (0.34)_{\mathrm{theor}}$

$\Delta Q_W \Rightarrow 2.0\ \sigma$

[20] A. I. Milstein and O. P. Sushkov, arXiv:hep-ph/0109257
[21] M. Yu. Kuchiev, V. V. Flambaum, arXiv:hep-ph/0206124
[22] A. A. Vasilyev et al., arXiv:physics/0112071

# New cesium PNC experiment

A new PNC experiment on cesium in a sapphire cell is underway at l'Ècole Normal Supérieur.[23] The experimental configuration consists of two collinear laser beams, pump and probe, and an $\boldsymbol{E}$ field in the same direction.

i) direct measurement of the PV asymmetry at the output of polarimeter

ii) calibration is lineshape independent

iii) the absence of Stark-M1 interference in a longitudinal field configuration, hence suppression of a source of systematics

iv) possibility of amplification when the probe beam propagates through an optically thick vapor

[23] J. Guéna et al., Quant. Semiclass. Opt. **10**, 733 (1998).

# Other cases

| Atom | Transition | Group |
|---|---|---|
| Fr | $7S_{1/2} \to 8S_{1/2}$ | Stony Brook |
| Yb | $(6s^2)\,{}^1S_0 \to (6s5d)\,{}^3D_1$ | Berkeley |
| Yb | $(6s6p)\,{}^3P_0 \to (6s6p)\,{}^3P_1$ | Berkeley |
| $Ba^+$ | $6S_{1/2} \to 5D_{3/2}$ | Seattle |
| Dy | $(4f^{10}5d6s)[10] \to (4f^9 5d^2 6s)[10]$ | Berkeley |
| Sm | $(4f^6 6s^2)\,{}^7F_J \to (4f^6 6s^2)\,{}^5D_{J'}$ | Oxford |

# Francium ($Z$=87)

- $E_{\text{PNC}}(\text{Fr})[7s_{1/2} \rightarrow 8s_{1/2}] \sim 15 \times E_{\text{PNC}}(\text{Cs})$
- $^{208-221}$Fr produced and trapped at SUNYSB[24]
- $T_{1/2} \sim 20$m for some isotopes ($^{212}$Fr)
- Spectrum established[25]
- Precision measurement of lifetimes and hyperfine constants[26]
- A microwave cavity experiment to measure the $I$-dependent PNC between ground-state hyperfine levels in Fr isotopes is proposed[27]

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

# Barium ion ($Z$=56)

A experiment is underway in Seattle to measure PNC in a single trapped barium ion.[28]

- Transition: $6s_{1/2} \rightarrow 5d_{3/2}$
- $E_{\text{PNC}} \sim 10^{-11} e\, a_0$ - competitive with Cs
- Seven naturally occurring isotopes, $\therefore$ 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[29] has been made on the spectroscopy of Ba$^+$

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[28] N. Fortson, Phys. Rev. Lett. **70**, 2383 (1993).
[29] 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)
- $E_{\text{PNC}}(\text{Yb})[^1S_0 \rightarrow ^3D_1] \sim 100 \times E_{\text{PNC}}(\text{Cs})$ [30]
- Mixing of $(6s5d)^3D_1$ with nearby $(6s6p)^1P_1$
- Only $I$-dependent terms $\Rightarrow E_{\text{PNC}}(\text{Yb})[^1S_0 \rightarrow ^3D_2]$
- Spectroscopy ($E2$, $M1$, $\beta$) of Yb studied[31,32]
- Progress and details given at Berkeley website [33]

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[30] D. DeMille, Phys. Rev. Lett. **74**, 4165 (1995).
[31] C. J. Bowers et al., Phys. Rev. A **59**, 3513 (1999).
[32] J. E. Stalnaker et al., Phys. Rev. A **65**, (2002).
[33] 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[34] 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[35] gave $H_W = 70(40)$ Hz — correlation dependent matrix element!

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[34] A.-T. Nguyen et al., Phys. Rev. A **56**, 3453 (1997).

[35] V. A. Dzuba et al., Phys. Rev. A **50**, 3812 (1994).

# Samarium ($Z$=62)

The optical rotation parameter $R\phi$ was measured[36] 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!

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

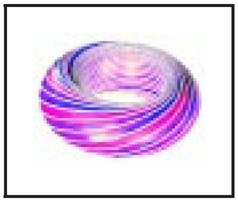
# Nuclear spin dependent terms

For a nucleus with a single unpaired nucleon, the axial current gives:

$$\boxed{H^{(2)} = -\frac{G}{\sqrt{2}}\, c_{2N}\, \frac{\kappa - 1/2}{I(I+1)}\, \alpha \cdot \mathbf{I}\, \rho_N(r)}$$

where $c_{2N} = c_{2p}$ or $c_{2n}$, $\kappa = \mp(I + 1/2)$ for $I = L \pm 1/2$. This term is $\sim 1/A$ as large as $H^{(1)}$.

Anapole Moment[37]

PNC in nucleus $\Rightarrow$ nuclear anapole: 

$$\boxed{H^{(a)} = \frac{G}{\sqrt{2}}\, K_a\, \frac{\kappa}{I(I+1)}\, \alpha \cdot \mathbf{I}\, \rho_N(r)}$$

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

# Spin-Dependent Interference Term

Interference between the hyperfine interaction $H_{\text{hf}}$ and $H^{(1)}$ gives yet another nuclear spin-dependent correction

$$\boxed{H^{(\text{int})} = \frac{G}{\sqrt{2}} K_{\text{int}} \frac{\kappa}{I(I+1)} \alpha \cdot \mathbf{I} \, \rho_N(r)}$$

- $c_{2p} \approx 0.047$ and $c_{2n} \approx -0.047$ arise from weak coupling of the electron vector current to the nucleon axial vector current.

- $K_a$ is the nuclear anapole coupling constant – value obtained from nuclear PNC calculations. $(K_a >> c_{2p})$

- $K_{\text{int}}$ from hyperfine structure measurements and atomic structure calculations.

# Results on anapole moment

$$\kappa_{\mathsf{exp}}(^{133}\mathsf{Cs}) = 0.112(16)$$
$$\kappa_{\mathsf{exp}}(^{205}\mathsf{Tl}) = 0.29(40)$$

The axial current term gives

$$\kappa_{\mathsf{SM}}(^{133}\mathsf{Cs}) = 0.0140$$
$$\kappa_{\mathsf{SM}}(^{205}\mathsf{Tl}) = -0.127$$

The interference term gives[38]

$$\kappa_{\mathsf{int}}(^{133}\mathsf{Cs}) = 0.0078$$
$$\kappa_{\mathsf{int}}(^{205}\mathsf{Tl}) = 0.044$$

Residual anapole contribution[39]

$$\kappa_a(^{133}\mathsf{Cs}) = 0.090(16)$$
$$\kappa_a(^{205}\mathsf{Tl}) = 0.38(40)$$

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

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

# Conclusions for Anapole Moment[39]

1. Measured anapole moments are not consistent 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.

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

What would be useful?

1. Improved thallium measurement

2. Moments from odd-neutron nuclei (Yb, Dy, $Ba^{+}$)