Atomic Parity Nonconservation: Status of Experiment/Theory

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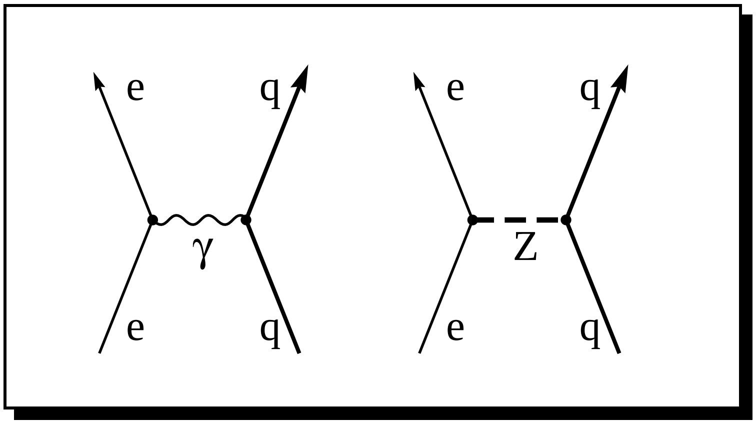
Abstract

Atomic parity nonconservation experiments and associated atomic structure calculations are reviewed with emphasis on those experiments designed to test the Standard Model of the Electroweak Interaction. Measurements of the nuclear anapole moment and comparisons with nuclear theory are also discussed.

Reminder



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

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

Consequence: Laporte's rule[1] violated!

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

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

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

- Precise (0.35%) measurement of E_{PNC}/β.[2]
- Re-measurement of β.[3]
- Re-analysis of accuracy of structure calculations.[3]
- Conclusion: 2.5 σ difference of Q_W^{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

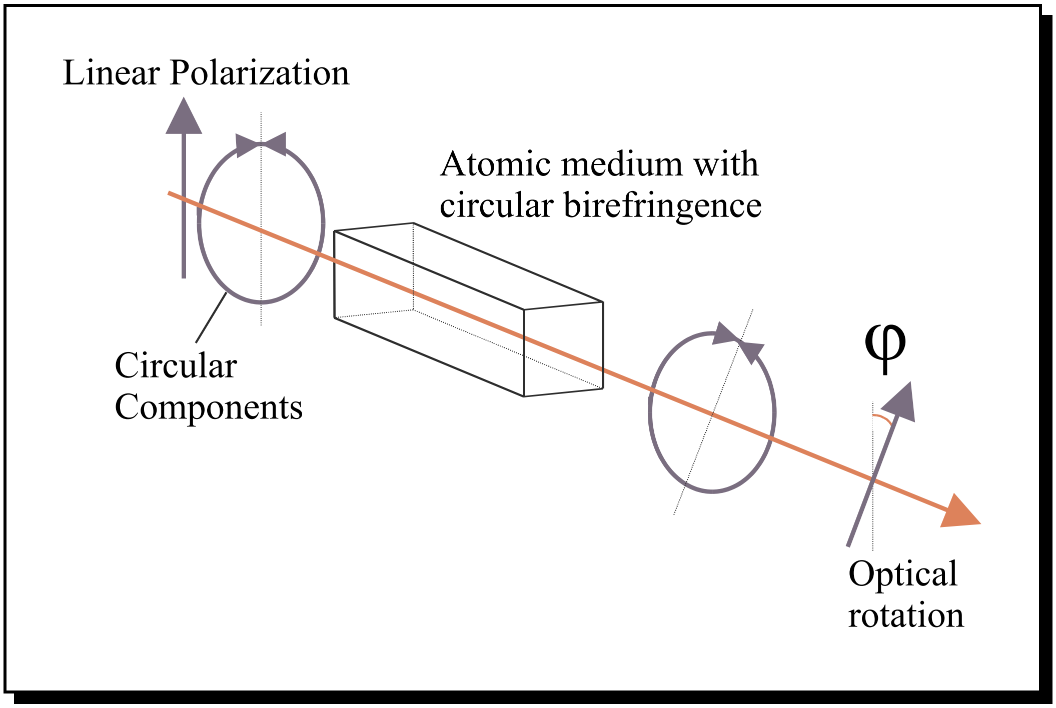
$$\boxed{R_\phi = \mathrm{Im}\left(E_{\mathrm{PNC}}\right)/M1}$$

where M1 is the magnetic-dipole transition matrix element.

Measured values of R_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)

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

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)

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

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

Better calculations for Tl needed!

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[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 $R_\phi(6p_{1/2} \rightarrow 6p_{3/2})$ 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 $6p_{1/2} \rightarrow 6p_{3/2}$ transition[7]

Details on Seattle group website.[9]

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[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_{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 β for this transition was also measured.[11]

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

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[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 $6s \to 7s$ 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)

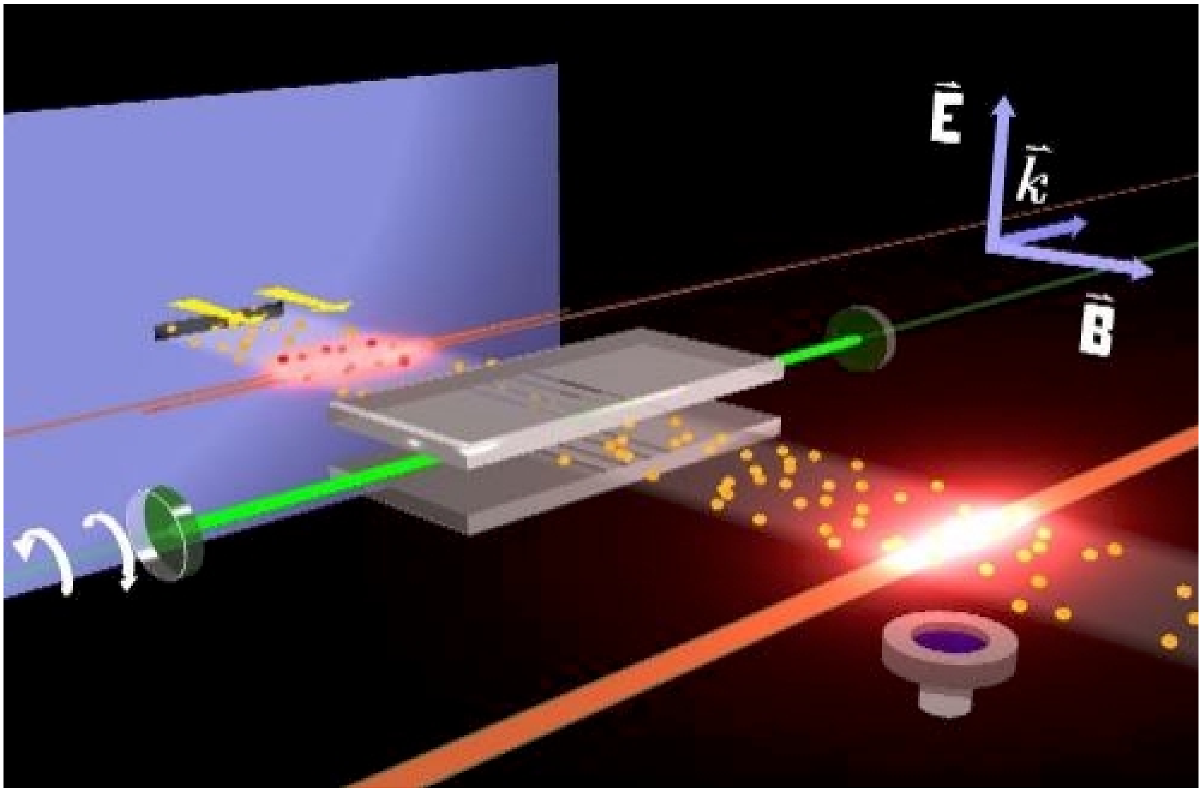
The vector current contribution from the last row is

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

Combining this with the value of β from Ref.[3], leads to

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

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.

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].)

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[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 $6s \rightarrow 7s$ amplitude in ^{133}Cs

Combining the calculations and the measurements, we find

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

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

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

What's Missing?

(A) Breit Interaction[14]

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

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[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_{PNC}
Coul	0.3457	-1.2726	-0.9269
Coul + V.P.	0.3471	-1.2778	-0.9307
Δ%	0.41%	0.41%	0.41%

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[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

Vertex Correction

There has been a great deal of controverssy concerning "structure effects" on the remaining "vertex" radiative corrections. In a vacuum, these corrections give

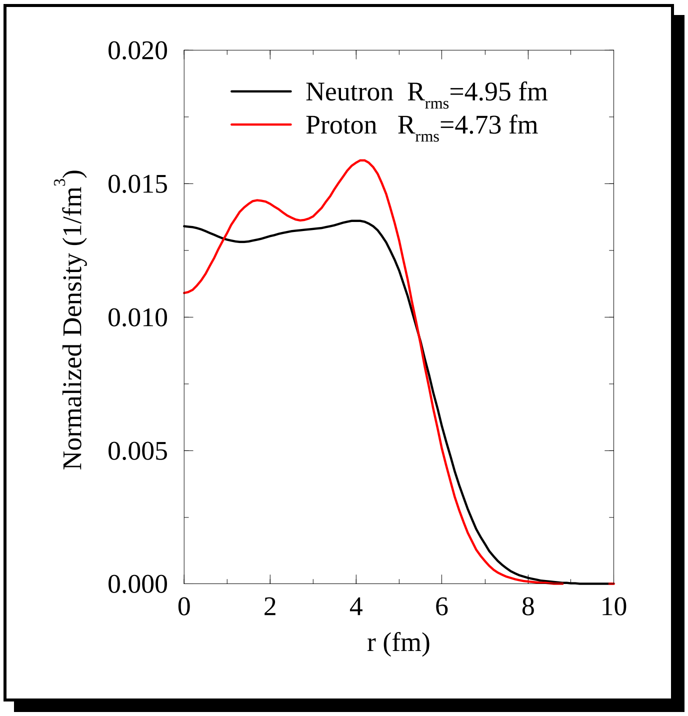
$$\delta Q_W = \frac{\alpha}{2\pi} Q_W \sim 0.1\% \; Q_W$$

Milstein & Sushkov (2001)	0.1%
Milstein, Sushkov & Terekhov (2002)	-0.85%
Kuchiev & Flambaum (2002)	-0.73%
Kuchiev (2002)	-0.9%

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.

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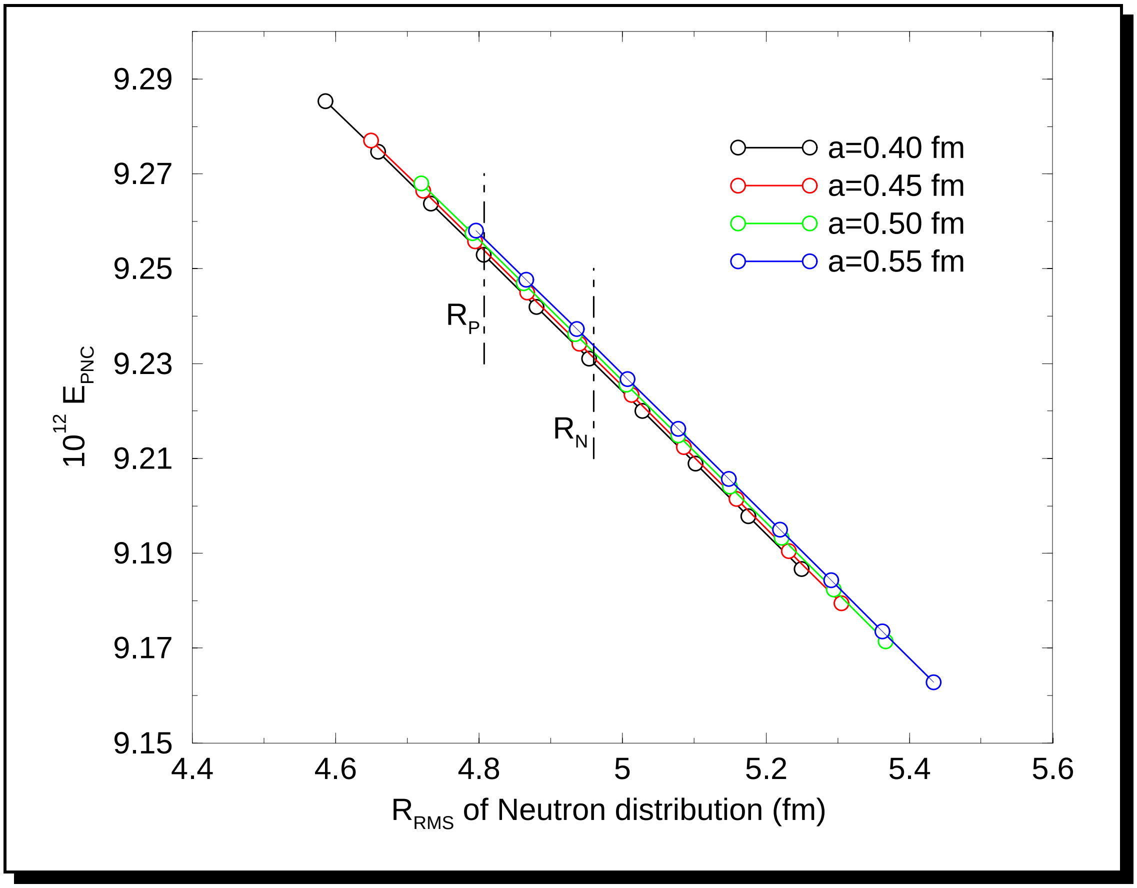
[16] D. Vretenar et al., Phys. Rev. C **62**, 045502 (2000).

RPA Calculations



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

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[17] A. Derevianko, Phya. Rev. A **65**, 052115 (2002)

[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+Vertex+"skin") corrections changes theory value to

$$\boxed{E_{\mathrm{PNC}} = -0.898 \;\pm 0.004 \; iea_0 \times 10^{-11}(-Q_W/N)}$$

Combining this with the experimental value of E_{PNC}/β, leads to an experimental value for the weak charge

$$\boxed{Q_W^{\mathrm{expt}}(^{133}\mathrm{Cs}) = -72.76 \pm (0.26)_{\mathrm{expt}} \pm (0.34)_{\mathrm{theor}}}$$

In agreement with the Standard Model

New cesium PNC experiment

A new PNC experiment on cesium in a sapphire cell is underway at l'Ècole Normal Supérieur.[20] 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

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

Other cases

Atom	Transition	Group
Fr	$7S_{1/2} \longrightarrow 8S_{1/2}$	Stony Brook
Yb	$(6s^2)\,{}^1S_0 \longrightarrow (6s5d)\,{}^3D_1$	Berkeley
Yb	$(6s6p)\,{}^3P_0 \longrightarrow (6s6p)\,{}^3P_1$	Berkeley
Ba$^+$	$6S_{1/2} \longrightarrow 5D_{3/2}$	Seattle
Dy	$(4f^{10}5d6s)[10] \longrightarrow (4f^{9}5d^{2}6s)[10]$	Berkeley
Sm	$(4f^{6}6s^{2})\,{}^7F_J \rightarrow (4f^{6}6s^{2})\,{}^5D_{J'}$	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[21]
- $T_{1/2} \sim 20$m for some isotopes (^{212}Fr)
- Spectrum established[22]
- Precision measurement of lifetimes and hyperfine constants[23]
- A microwave cavity experiment to measure the I-dependent PNC between ground-state hyperfine levels in Fr isotopes is underway.[24]

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[21] J. E. Simsarian et al., Phys. Rev. Lett. **76**, 3522 (1996).

[22] J. E. Simsarian et al., Opt. Lett. **21**, 1939 (1996).

[23] J. S. Grossman et al., Physica Scripta T**86**, 16 (2000).

[24] S. Aubin et al., Proceedings of International Conference on Laser Spectroscopy, 2001.b

Barium ion (Z=56)

A experiment is underway in Seattle to measure PNC in a single trapped barium ion.[25]

- 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[26] has been made on the spectroscopy of Ba^{+}

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[25] N. Fortson, Phys. Rev. Lett. **70**, 2383 (1993).

[26] 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)
- $E_{\text{PNC}}(\text{Yb})[^1S_0 \to ^3 D_1] \sim 100 \times E_{\text{PNC}}(\text{Cs})$ [27]
- Mixing of $(6s5d)^3D_1$ with nearby $(6s6p)^1P_1$
- Only I-dependent terms $\Rightarrow$ $E_{\text{PNC}}(\text{Yb})[^1S_0 \to ^3 D_2]$
- Spectroscopy ($E2$, $M1$, β) of Yb studied[28,29]
- Progress and details given at Berkeley website [30]

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

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

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

Samarium (Z=62)

The optical rotation parameter $R\phi$ was measured[33] 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 $(4f^6 6s6p)$ 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!

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

Nuclear spin dependent terms

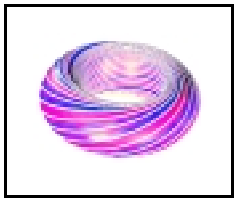
For a nucleus with a single unpaired nucleon, the axial current gives:

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

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[34]

PNC in nucleus ⇒ nuclear anapole:



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

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

Spin-Dependent Interference Term

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

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

- $c_{2p} \approx 0.047$ 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_{int} from hyperfine structure measurements and atomic structure calculations.

Results on anapole moment

$$\kappa_{\text{exp}}(^{133}\text{Cs}) = 0.112(16)$$

$$\kappa_{\text{exp}}(^{205}\text{Tl}) = 0.29(40)$$

The axial current term gives

$$\kappa_{\text{SM}}(^{133}\text{Cs}) = 0.0140$$

$$\kappa_{\text{SM}}(^{205}\text{Tl}) = -0.127$$

The interference term gives[35]

$$\kappa_{\text{int}}(^{133}\text{Cs}) = 0.0078$$

$$\kappa_{\text{int}}(^{205}\text{Tl}) = 0.044$$

Residual anapole contribution[36]

$$\kappa_{a}(^{133}\text{Cs}) = 0.090(16)$$

$$\kappa_{a}(^{205}\text{Tl}) = 0.38(40)$$

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

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

Conclusions for Anapole Moment

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. Anapole moment experiments for odd-neutron nuclei (Fr, Yb, Dy, Ba^+)