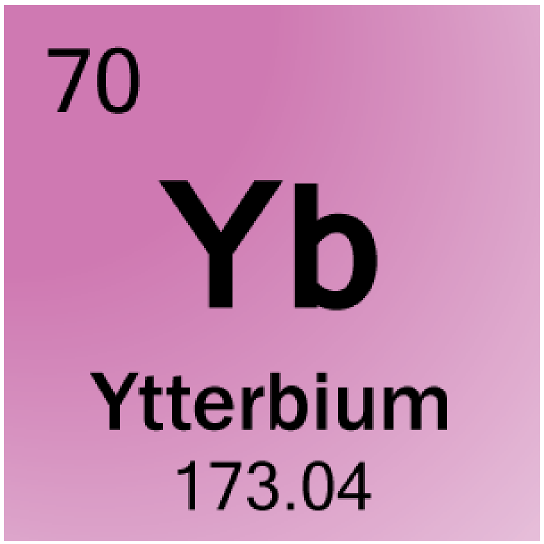
Parity violation in Yb and Dy

Dionysis Antypas

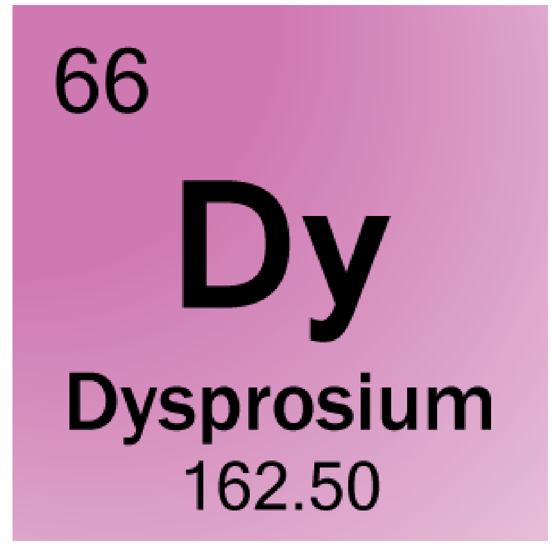
PVES 2018

Helmholtz-Institut Mainz

Atomic Parity Violation at the Helmholtz-Institut Mainz



Dionysis Antypas
Anne Fabricant

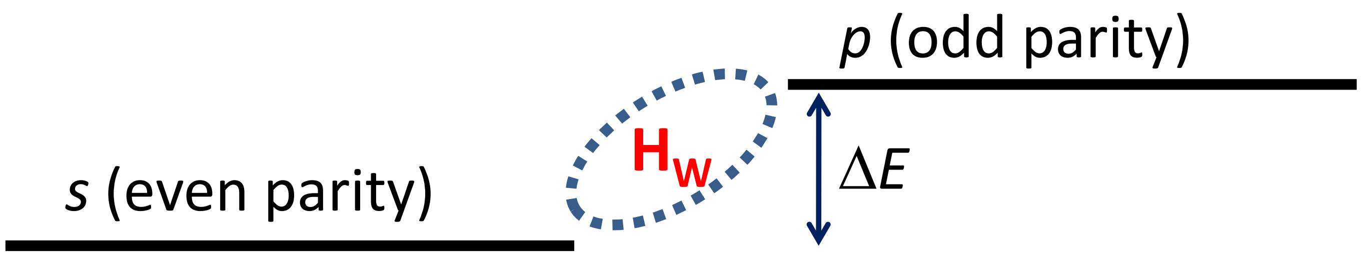


Arijit Sharma
Lykourgos Bougas
Peter Leyser

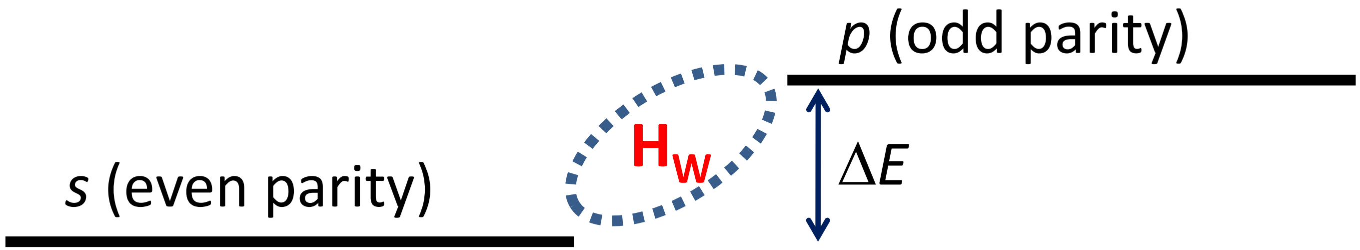
Outline

- Background & motivations
- Yb experiment, new results & future
- Dy experiment

The weak interaction mixes atomic states of opposite nominal parity (s & p)



The weak interaction mixes atomic states of opposite nominal parity (s & p)



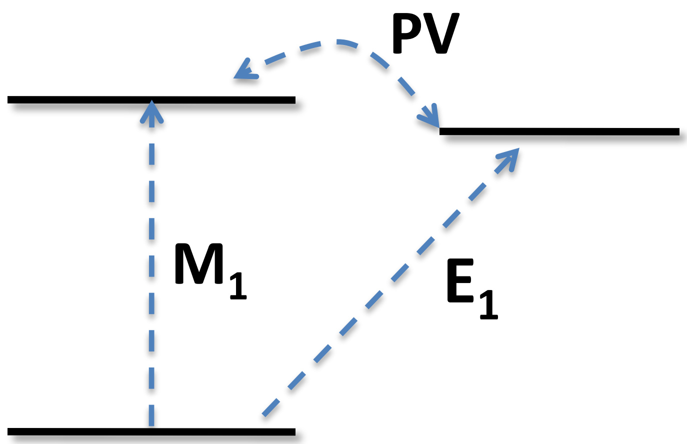
$$s \rightarrow s + i\varepsilon p;\; p \rightarrow p + i\varepsilon s$$

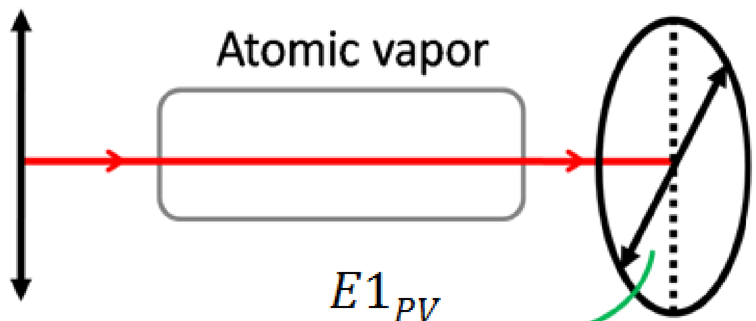
$$\varepsilon = \frac{\langle s | H_W | p \rangle}{\Delta E} \sim \frac{RZ^3}{\Delta E}$$ - the Bouchiat Law

Atomic PV **Enhancement**:

- Heavy atoms (high Z)
- Small ΔE

Types of atomic PV experiments

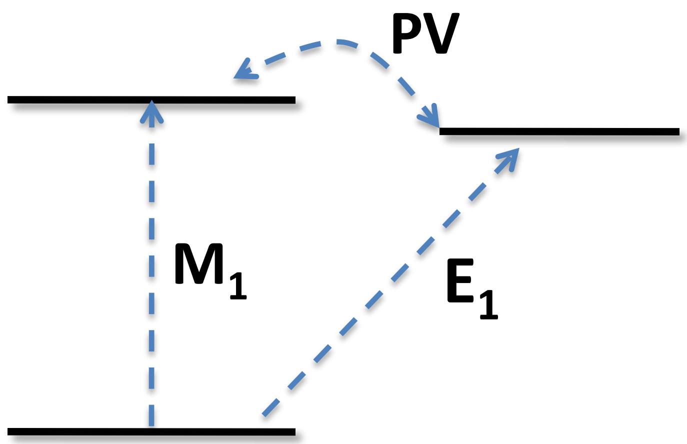


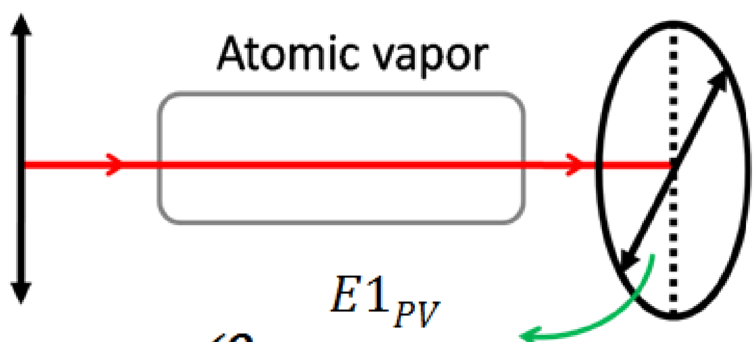


$$\varphi \sim \frac{E1_{PV}}{M1}$$

- 100% contrast (small signal)
- No reversals

Types of atomic PV experiments





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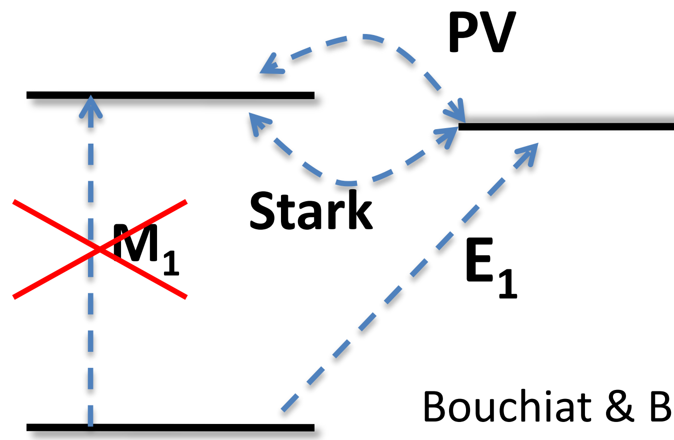


Bouchiat & Bouchiat

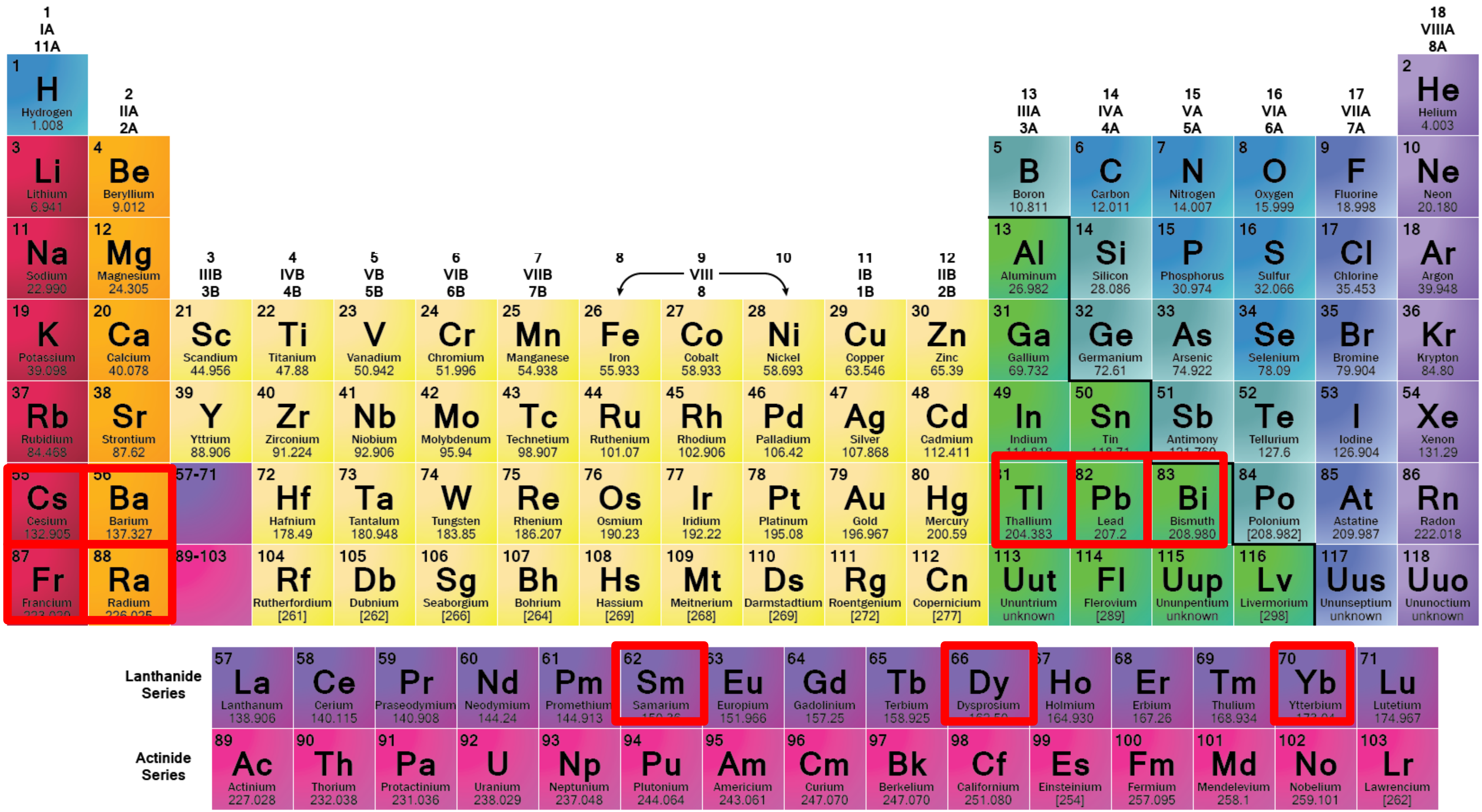
$$W_{\pm} = |A_{Stark} + A_{PV}|^2$$

$$\approx \underbrace{A_{Stark}^2}_{P-conserving} \underbrace{\pm 2A_{Stark} \cdot A_{PV}}_{P-violating}$$

$$Asymmetry = \frac{W_+ - W_-}{W_+ + W_-} \sim \frac{E1_{PV}}{E1_{Stark}}$$

- Small contrast on large signal
- Many reversals for systematics

Experimental atomic PV studies

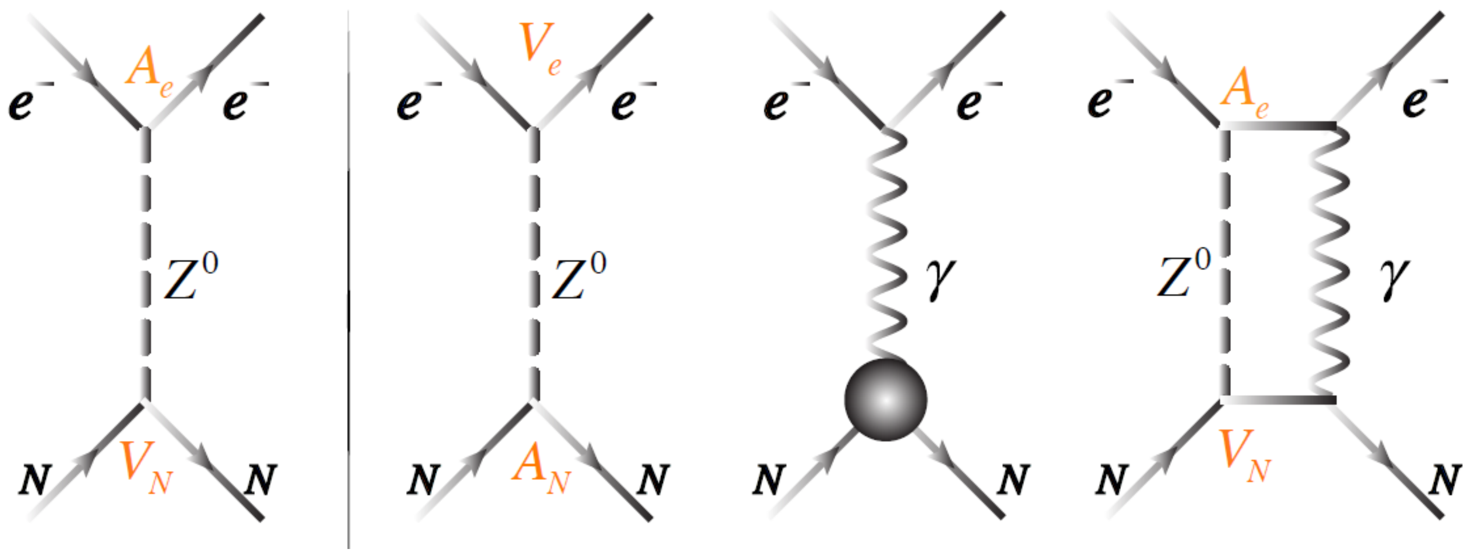


...and a molecule: BaF

Atomic parity violation: Main processes

Nuclear-spin Independent (NSI)

Nuclear-spin dependent (NSD)



Weak neutral currents

Weak neutral currents

Anapole moment-hadronic PV

Hyperfine corrections to weak neutral currents

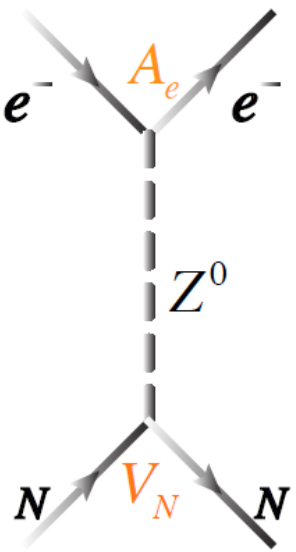
$$H_{NSI} = Q_W \frac{G_F}{\sqrt{8}} \gamma_5 \rho(r)$$

$$H_{NSD} = \frac{G_F}{\sqrt{2}} \left(\eta_{axial} + \eta_{AM} + \eta_{hf}\right)(\boldsymbol{\alpha} \cdot \boldsymbol{I})\rho(r)$$

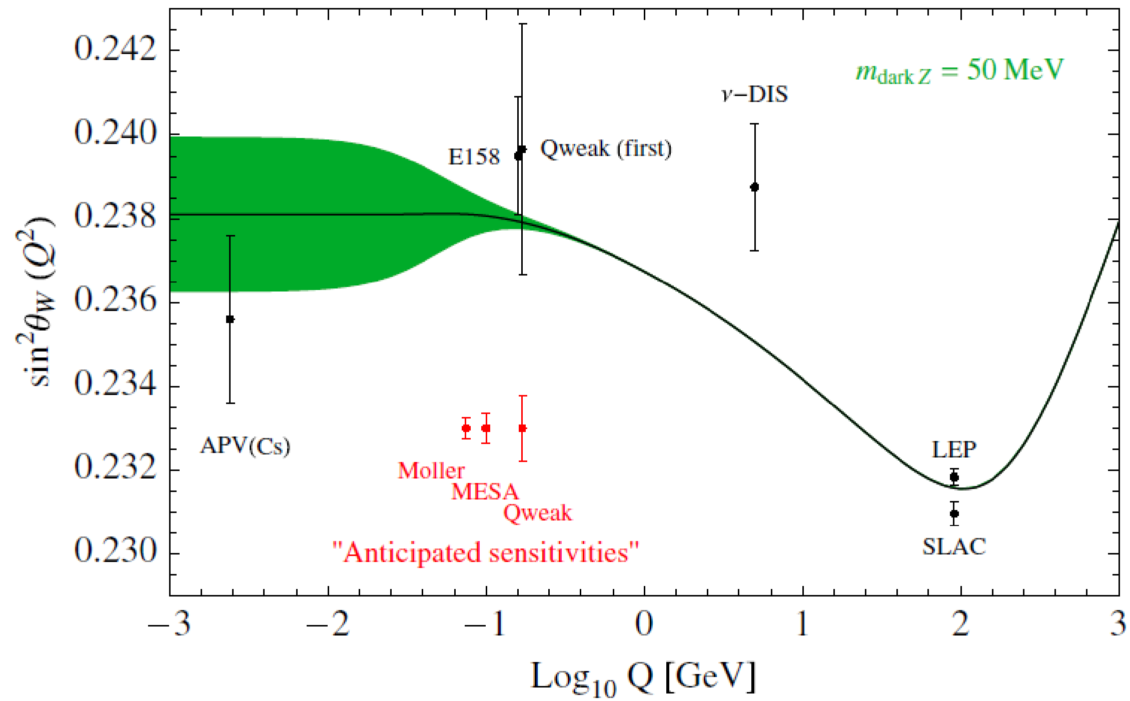
Size of NSD effects depend on Z & type of valence nucleon

Safranova et al. arXiv:1710.01833

Nuclear spin-independent atomic PV



$$H_{NSI} = Q_W \frac{G_F}{\sqrt{8}} \gamma_5 \rho(r)$$

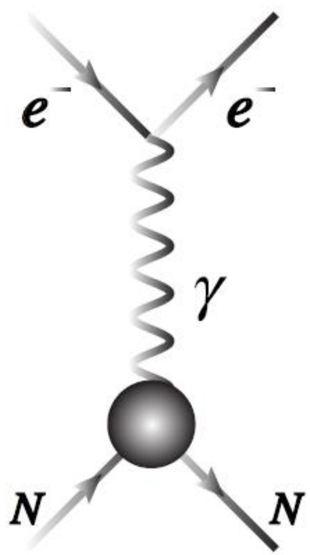


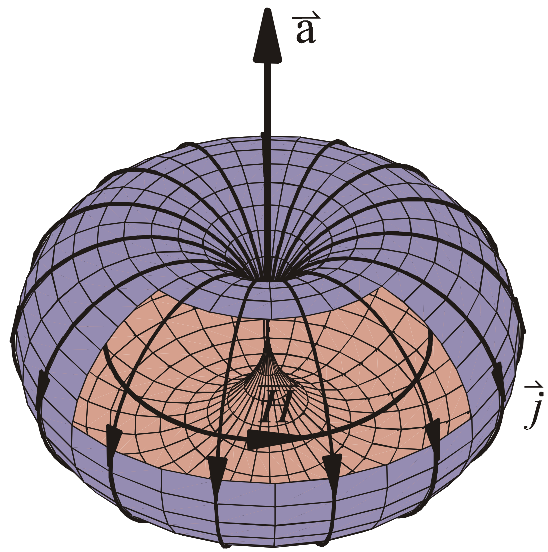
Davoudiasl et al, Phys. Rev. D 89, 1402.3620

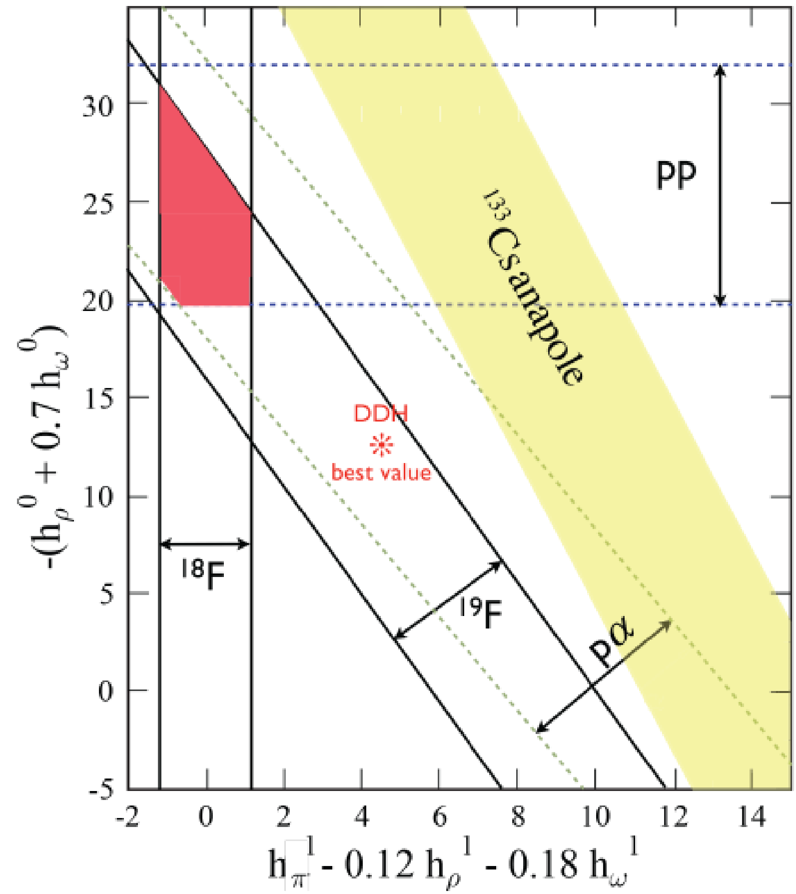
- Probe the nuclear weak charge Q_W
- Lower bound on new Z bosons
- Probe of the "dark" sector: dark boson, cosmic parity violation (axions, ALPs)

$$Q_W \approx -N + Z\cdot(1\text{-}4\sin^2\vartheta_W)$$

Nuclear spin-dependent atomic PV: Anapole







$$H_{AM} = \frac{G_F}{\sqrt{2}} \eta_{AM} (\boldsymbol{\alpha} \cdot \boldsymbol{I}) \rho(r)$$

Safranova et al. arXiv:1710.01833

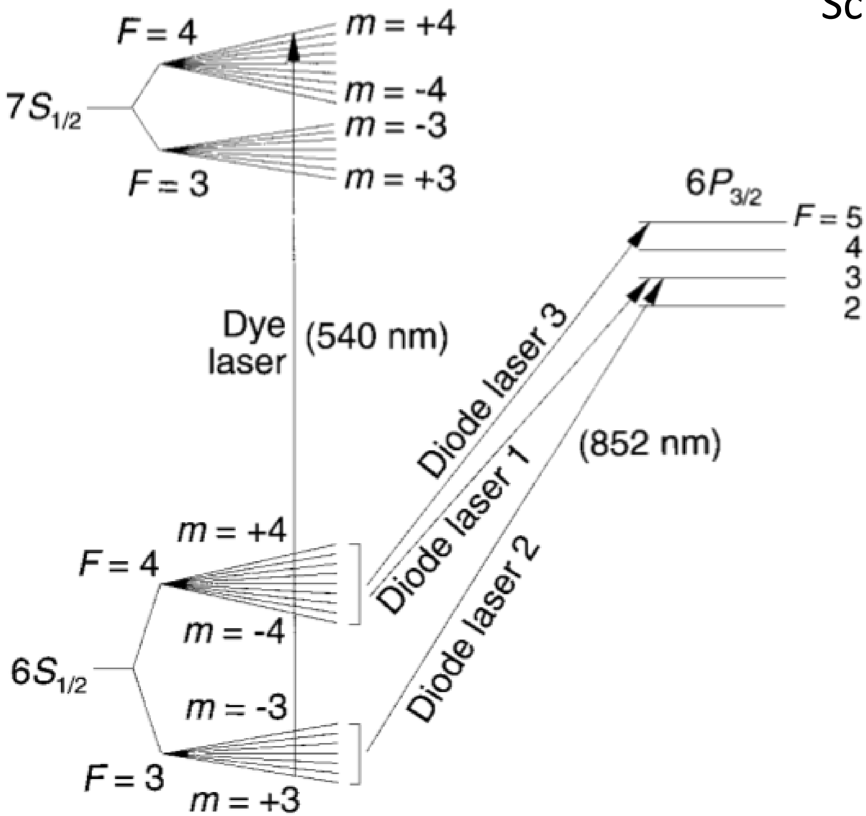
Anapole:

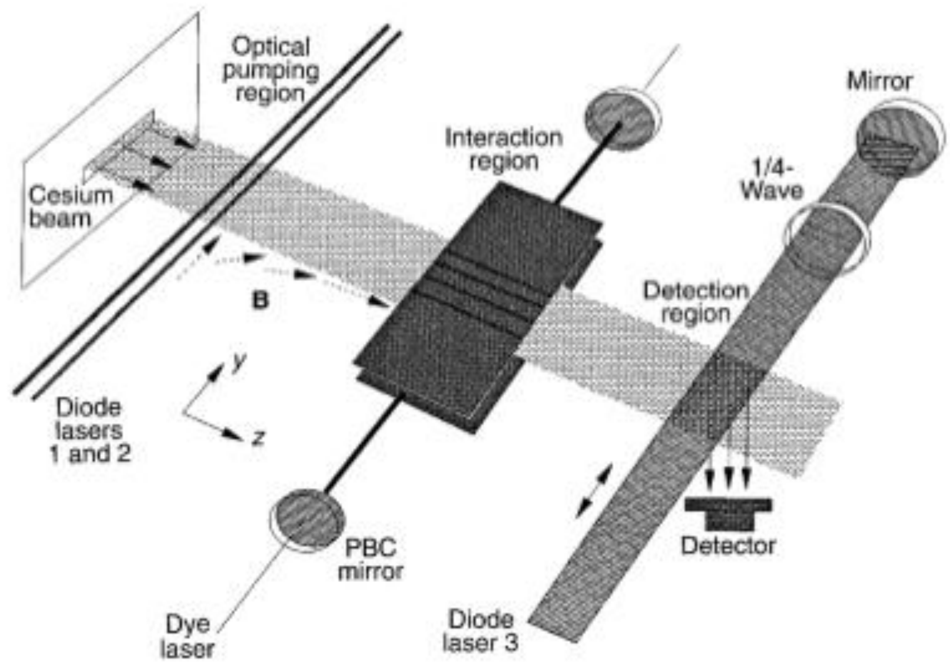
- P-odd E/M moment from intranuclear PV
- Probe of weak meson-nucleon couplings (hadronic PV)

The cesium experiment

Based on Stark interference technique proposed by Bouchiat & Bouchiat in the 70s

C. S. Wood *et al.*
Science ***275,*** *1759 (1997)*





The cesium results

Experiment

$$-\mathrm{Im}(E1_{PNC})/\beta = \begin{cases} 1.6349(80)\ \mathrm{mV/cm} \\ 1.5576(77)\ \mathrm{mV/cm} \end{cases}$$

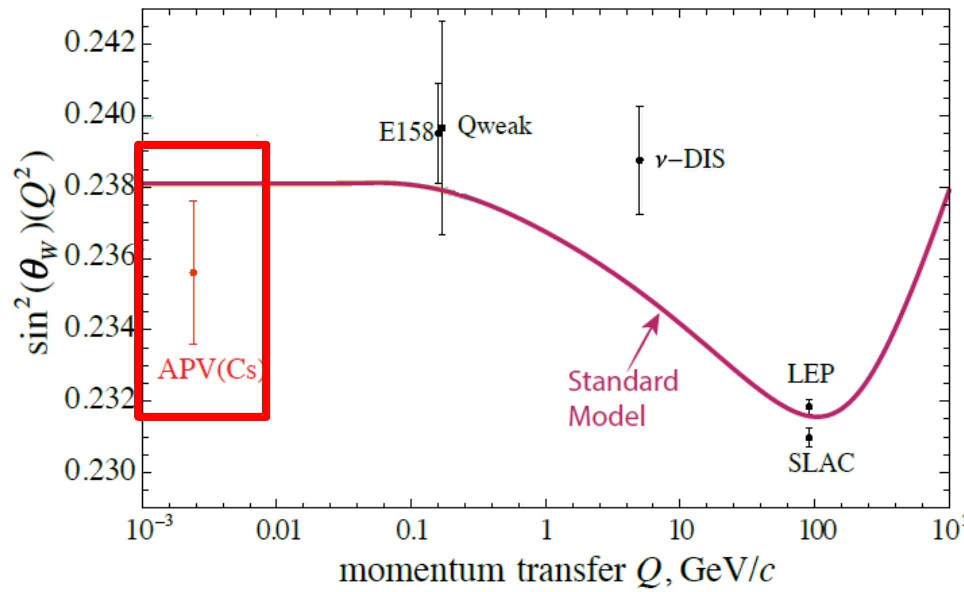
Atomic structure calculations

$E1_{PNC}$=0.8977(40) x 10^{-11} $i(-Q_W/N)$

Inferred Q_W = -72.58 $(29)_{exp}(32)_{theory}$

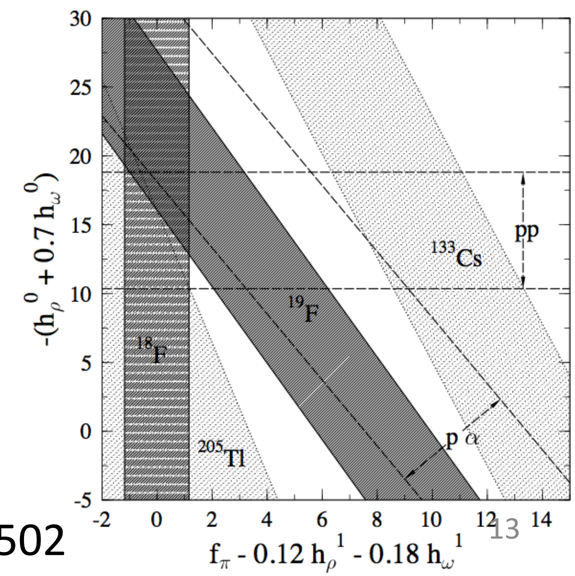
$Q_W = -N + Z\cdot(1-4\sin^2\vartheta_W) +$ $\Delta Q_{New\ Physics}$

V.A. Dzuba et al, PRL 109, 203003 (2012)



Davoudiasl et al, Phys. Rev. D 89, 1402.3620

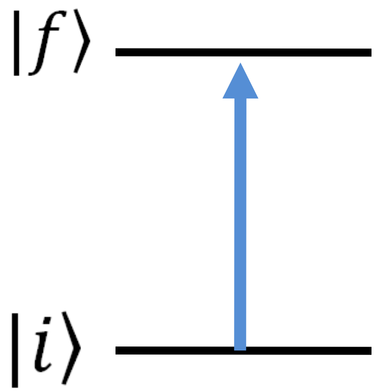
- Constrain new physics at tree-level & through radiative corrections
- Constraints on weak meson couplings



Haxton, et. al. PRC, VOLUME 65, 045502

Isotopic ratios in atomic PV

- APV measures: $E1_{PV} = k_{PV} Q_W$



$$E1_{PV} = \langle f | D | i \rangle$$

Element	δk_{PV}
Cs	0.4 %
Yb	10 %

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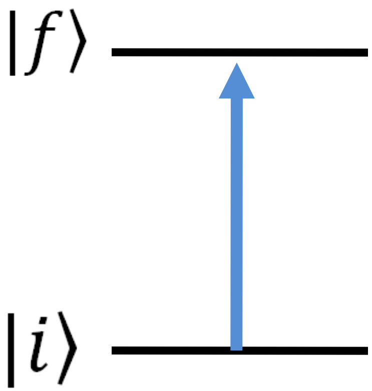

$$E1_{PV} = \langle f | D | i \rangle$$

Element	δk_{PV}
Cs	0.4 %
Yb	10 %

- Atomic PV calculation errors cancel in isotopic ratios
  Dzuba, Flambaum, and Khriplovich, Z. Phys. D 1, 243 (1986)

$$R = \frac{E1'_{PV}}{E1_{PV}} = \frac{Q'_W}{Q_W}$$

Isotopic ratios and neutron skins

- Limitation to isotopic ratio method: enhanced sensitivity to the neutron distribution $\rho_n(r)$
  Fortson, Pang, Wilets, PRL **65**, 2857 (1990)

$$\bar{Q}_W = -N\underline{q_n} + Z\underline{q_p}(1 - 4\sin^2\theta_W) + \Delta Q_{\text{new}}$$

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- Atomic PV ⟺ Neutron distributions

$$\frac{E1_{PV}}{E1'_{PV}} = 1 + \frac{\Delta N}{N} + \boxed{\frac{3}{7}(aZ)^2\,\frac{[\Delta R'_{ns} - \Delta R_{ns}]}{R_p}}$$

skin contribution for ^{170}Yb - ^{176}Yb isotopes ~ 0.1%

Isotopic ratios and neutron skins

[PHYSICAL REVIEW C **79, 035501 (2009)**]

Dispelling the curse of the neutron skin in atomic parity violation

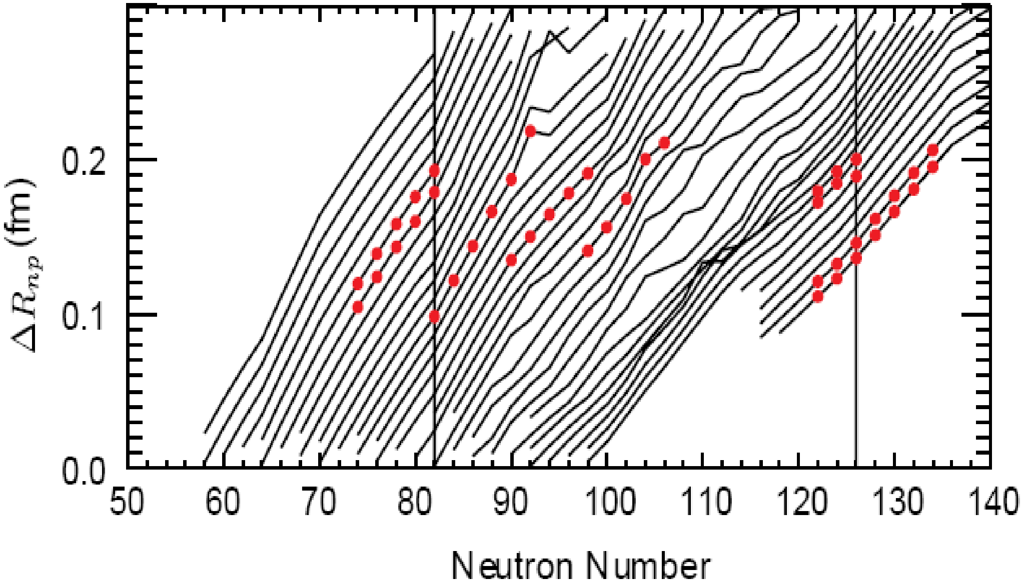
B. A. Brown,[1] A. Derevianko,[2,3] and V. V. Flambaum[3]

[1]*Department of Physics and Astronomy, and National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824-1321, USA*

[2]*Department of Physics, University of Nevada, Reno, Nevada 89557*

[3] *School of Physics, University of New South Wales, Sydney 2052, Australia*

- Neutron-skin effects in different isotopes are **correlated**



PV in ytterbium

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- **Large** APV effect (DeMille *et al*, 1995 - Tsigutkin *et al,* 2009)

PV in ytterbium

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- 7 stable isotopes (A=168, 170-174,176)

Isotope	NA (%)	I
^{174}Yb	31.8	0
^{172}Yb	21.8	0
^{176}Yb	12.8	0
^{173}Yb	16.1	5/2
^{171}Yb	14.3	1/2
^{170}Yb	3.04	0
^{168}Yb	0.13	0

- PNC on chain of isotopes → neutron distributions

→ Physics beyond Standard Model

PV in ytterbium

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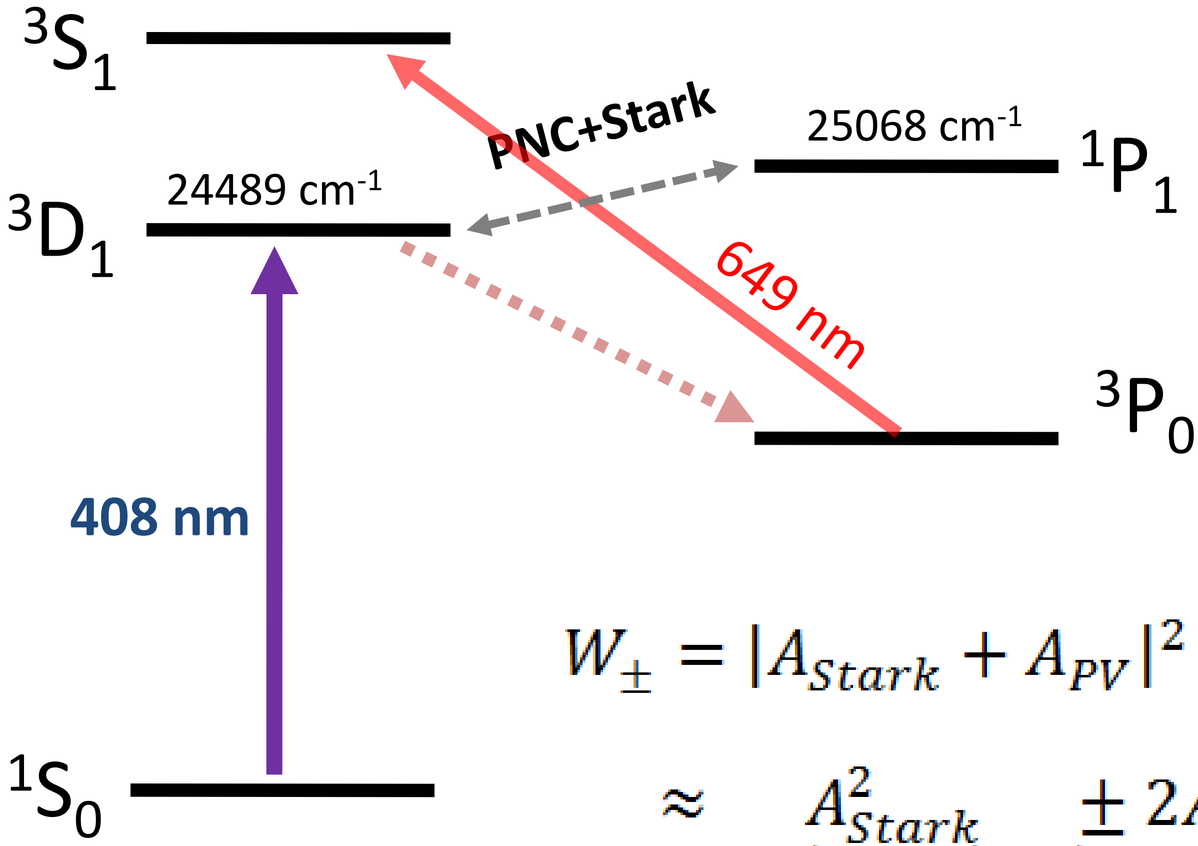
- PNC on chain of isotopes → neutron distributions

  → Physics beyond Standard Model

- Two isotopes with nuclear spin → hadronic weak interaction

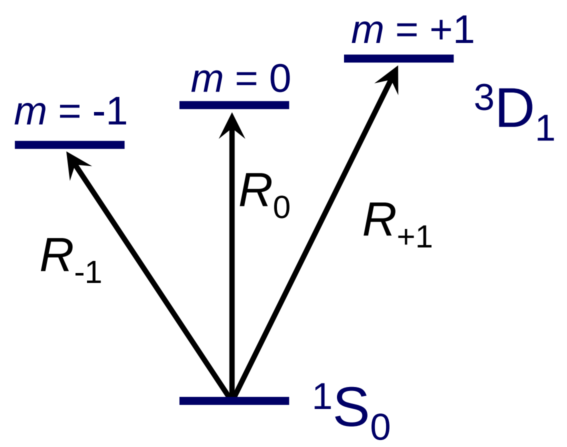
The Yb PV experiment

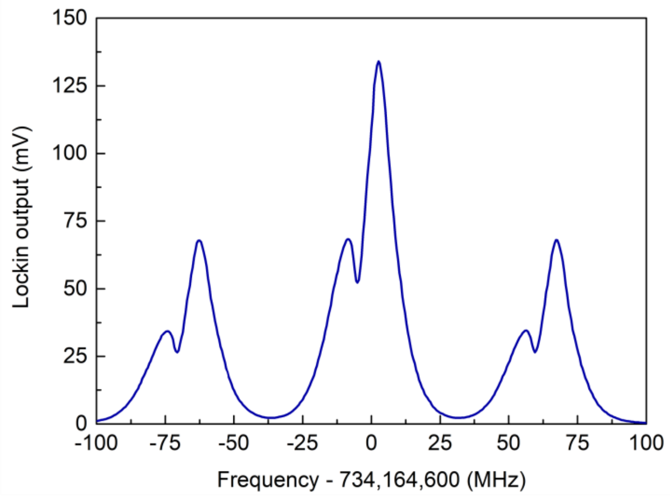


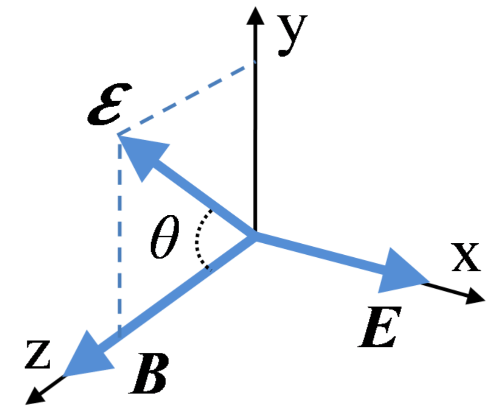
$$W_\pm = |A_{Stark} + A_{PV}|^2$$

$$\approx \underbrace{A_{Stark}^2}_{P-conserving} \underbrace{\pm 2A_{Stark} \cdot A_{PV}}_{P-violating}$$

The Yb PV experiment







Rotational invariant:

$$\left(\vec{\varepsilon}\cdot\vec{B}\right)\left(\vec{E}\times\vec{\varepsilon}\cdot\vec{B}\right)$$

$$R_0 \propto \left|A_{Stark} + A_{PNC}\right|^2 \approx \beta^2 E^2 \sin^2\theta + 2E\beta\zeta\cos\theta\sin\theta$$

Stark-PV interference

PV asymmetry:
$2\zeta/\beta E_0 \approx 5\cdot 10^{-5}$

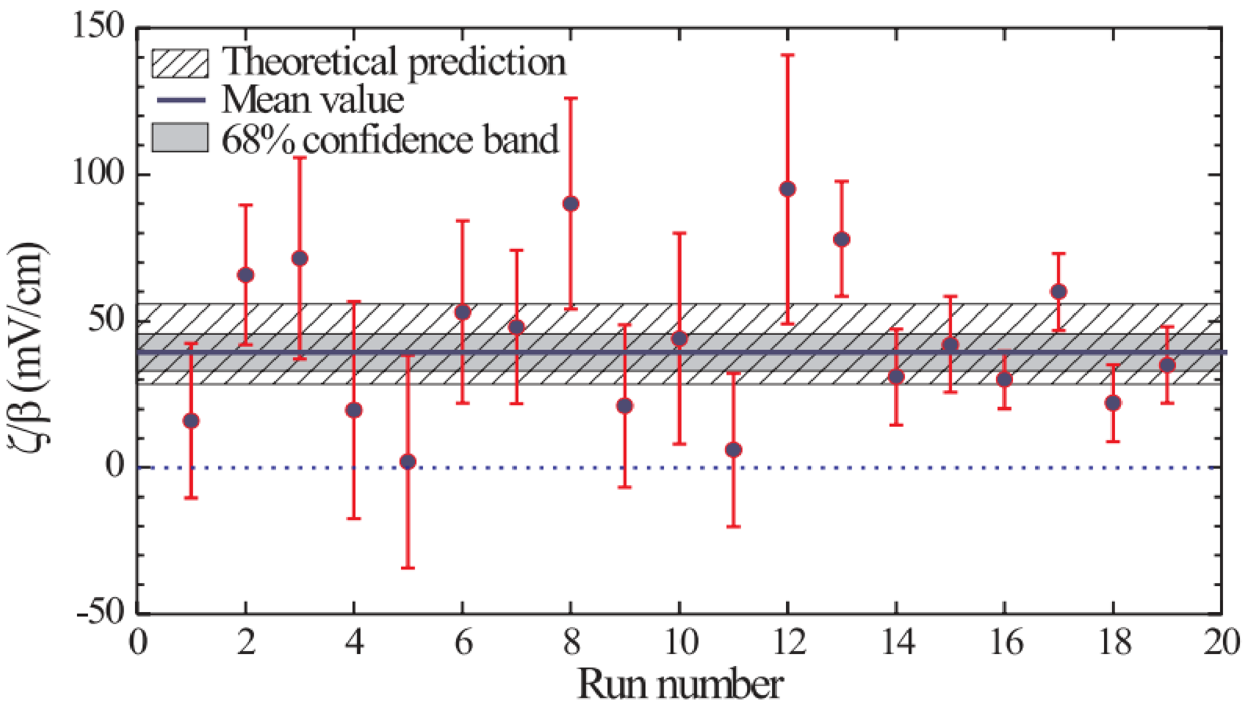
Parity reversals: E (20 Hz) and θ (0.2 Hz)

^{174}Yb PV results at UC Berkeley

Selected for a Viewpoint in *Physics*
PRL **103,** 071601 (2009) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2009

Observation of a Large Atomic Parity Violation Effect in Ytterbium

K. Tsigutkin,[1,*] D. Dounas-Frazer,[1] A. Family,[1] J. E. Stalnaker,[1,†] V. V. Yashchuk,[2] and D. Budker[1,3]

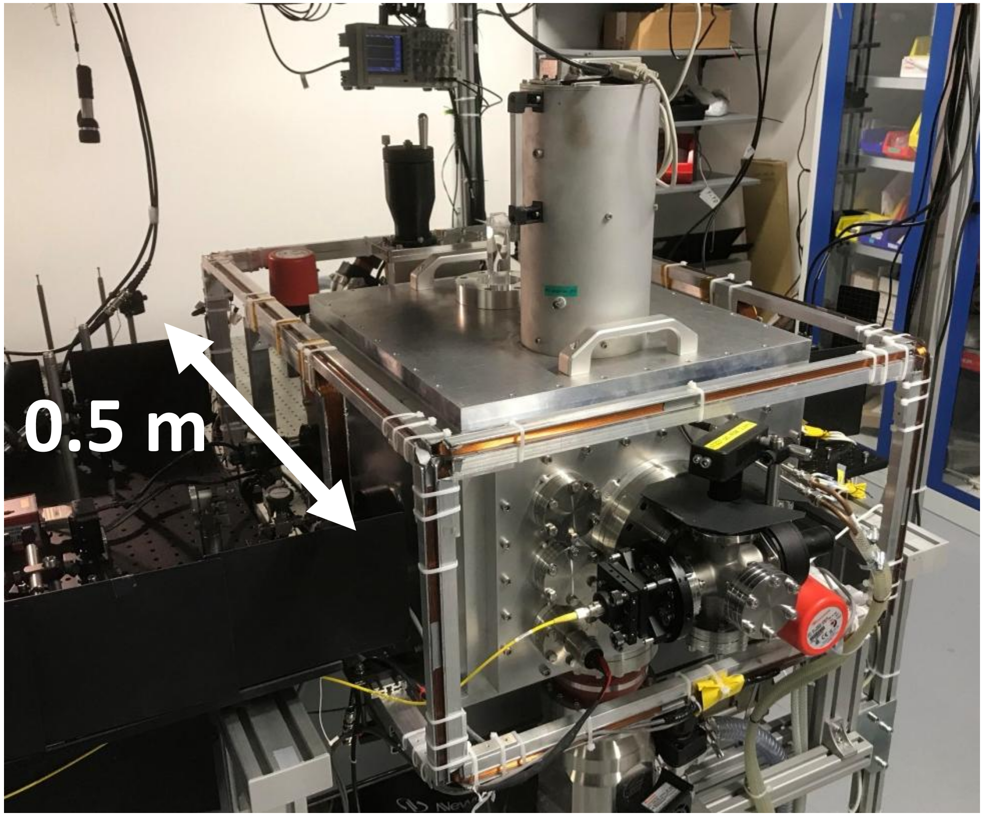


Mean value: $39(4)_{\mathrm{stat}}(5)_{\mathrm{syst}}$ mV/cm, $|\zeta| = 8.7 \pm 1.4 \times 10^{-10} ea_0$

Yb reincarnation in Mainz

New apparatus

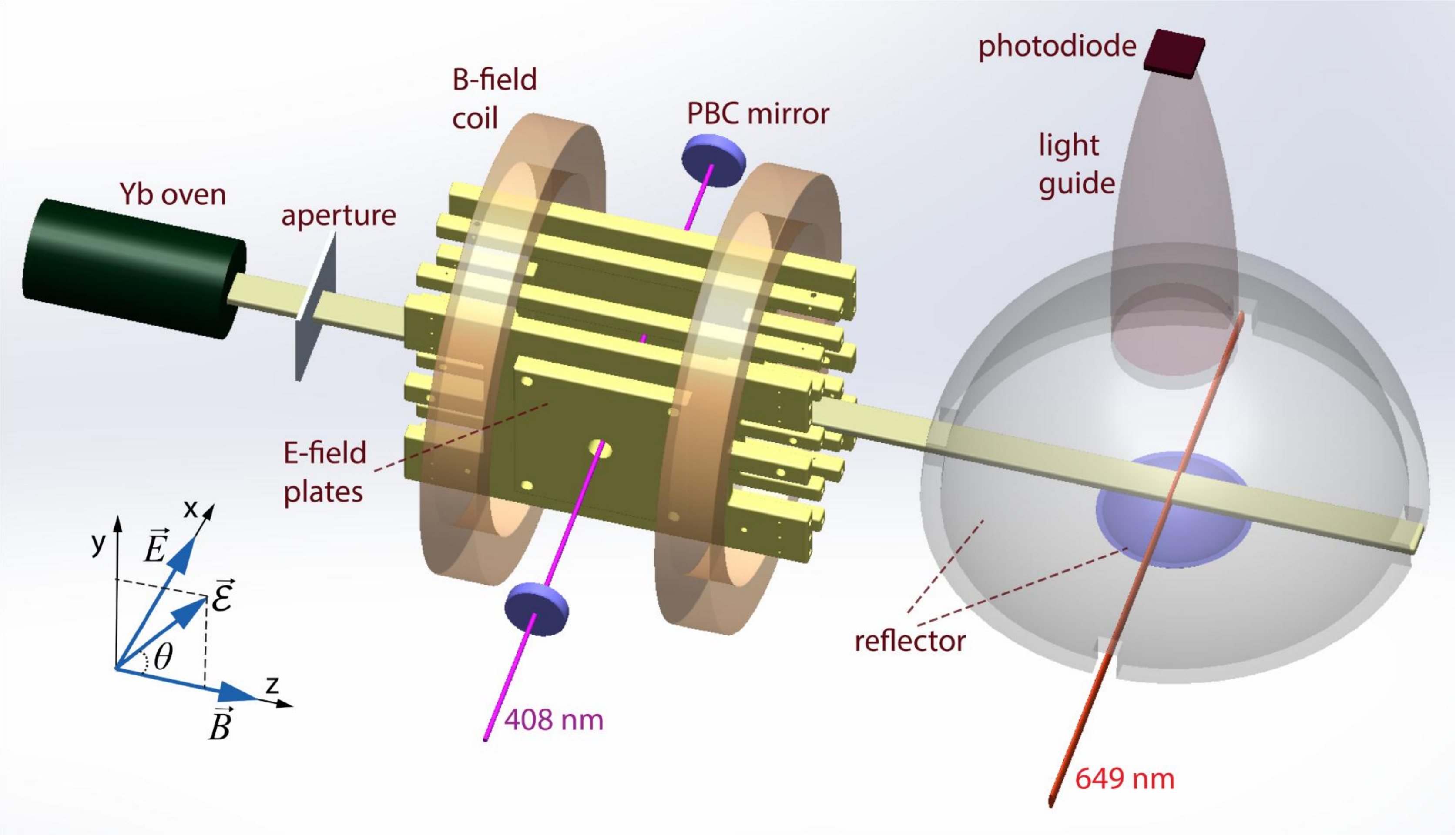
- Newly built vacuum system
- More powerful and frequency stable laser system
- More precise control of fields applied in interaction region
- 20 times better SNR



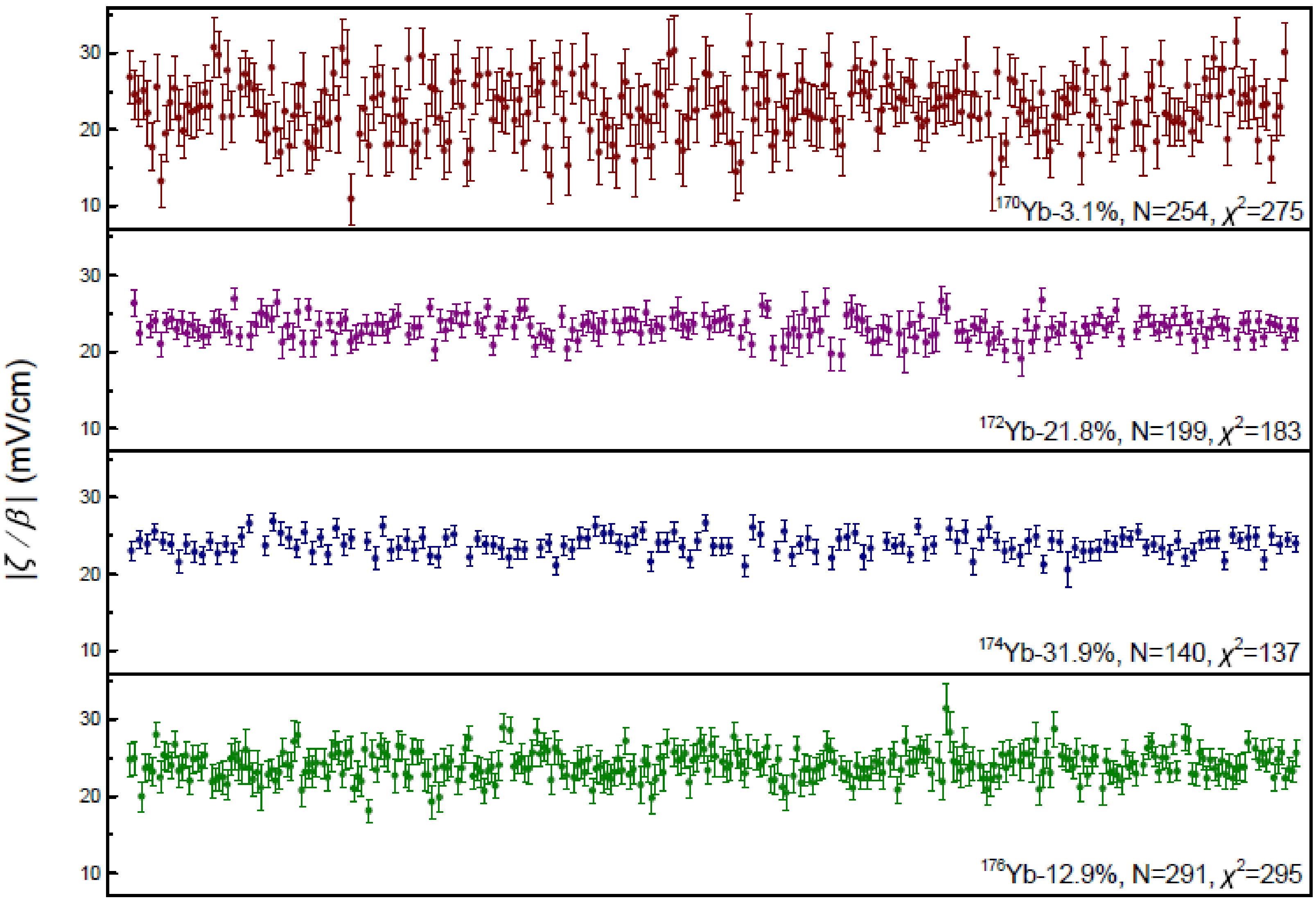
Mainz Roadmap

- Verify expected isotopic dependence of PV (0.5% accuracy) ✓
- Probe spin-dependent PV (sub-0.1 %)
- Neutron distributions/new physics (sub-0.1%)

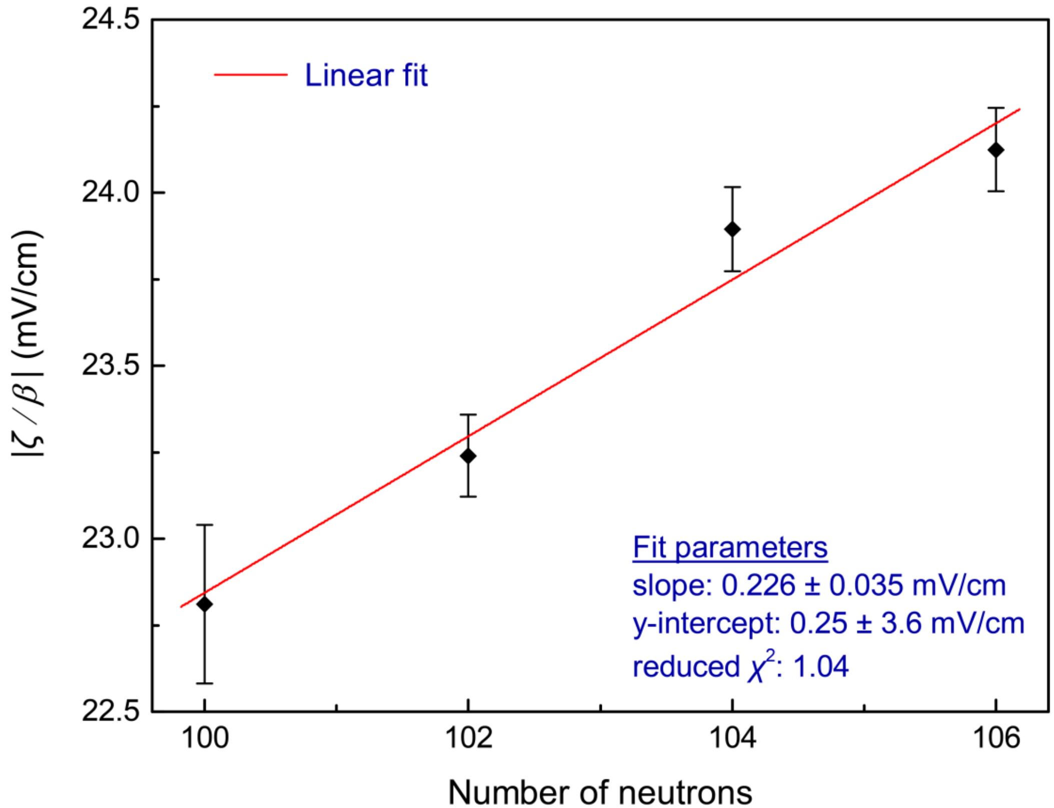
Yb atomic beam apparatus



New Yb PV data in 4 spin-zero isotopes (450 hrs)



First observation of isotopic variation of atomic PV



0.5% single isotope accuracy

arXiv:1804.05747

SM: $Q_W \approx -N + Z(1 - 4\sin^2\theta_W) \rightarrow$ 1% change per neutron around N=103

Observation: 0.96(15) % change per neutron

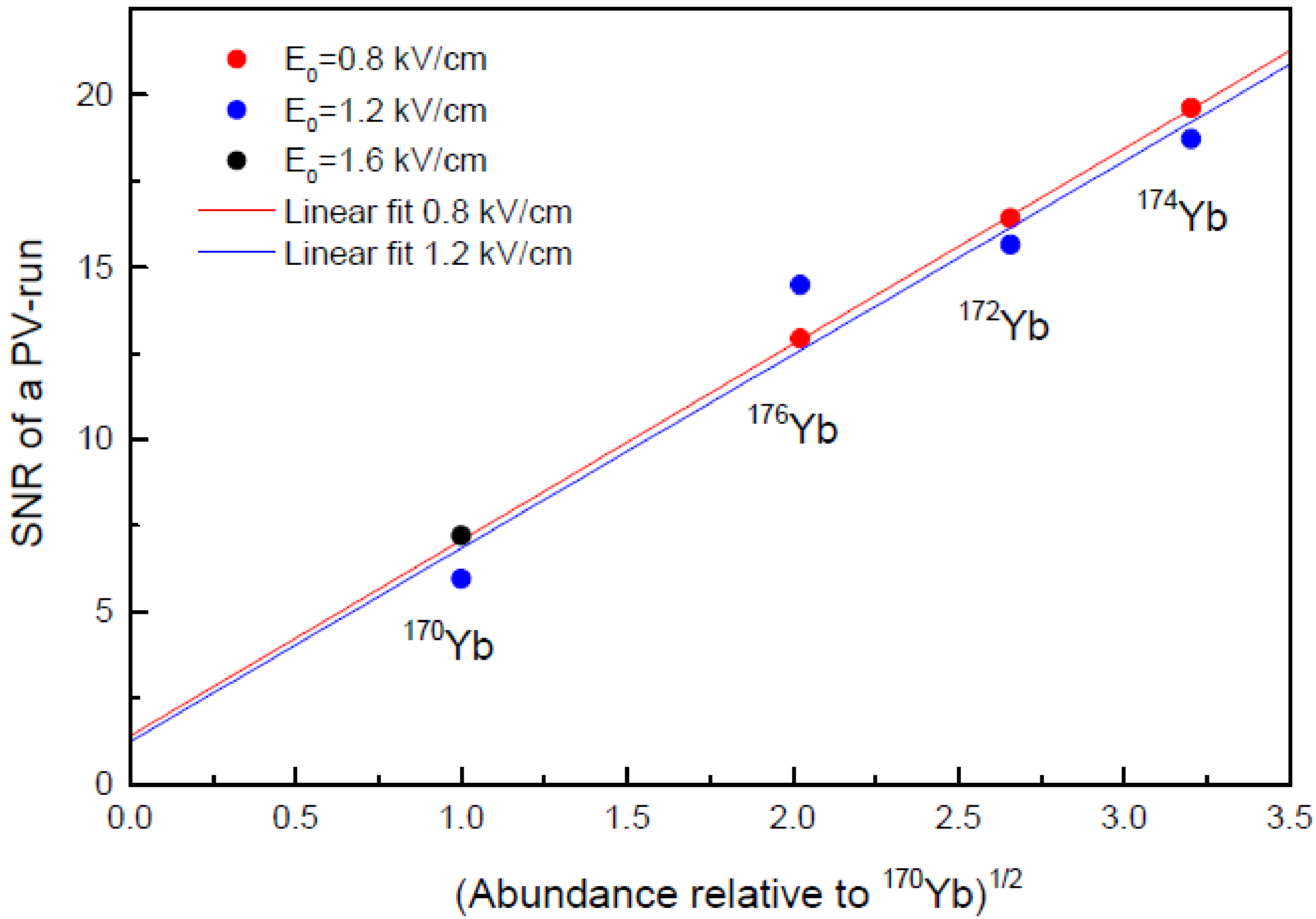
Single isotope measurement uncertainties

Systematic uncertainties	Error (%)
Harmonics ratio calibration	0.22
Polarization angle	0.1
High-voltage measurements	0.06
Transition saturation correction	0.05 (0.09 for ^{170}Yb)
Field-plate spacing	0.04
Photodetector response calibration	0.02
Stray fields & field-misalignments	0.02
Total systematic	**0.26**
Statistical uncertainty	**0. 42 (0.9 for ^{170}Yb)**
Total uncertainty	**0.5 (0.9 for ^{170}Yb)**

False-PV related (1 year of work) → Stray fields & field-misalignments

Isotopic comparison **bonus**:
decreased sensitivity to systematics

Yb PV measurement sensitivity



Next: spin-dependent PV with Yb

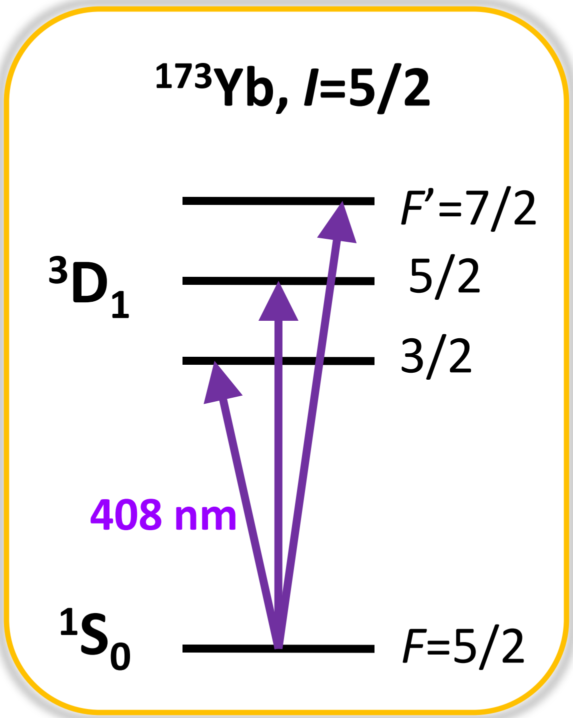


Table 1
Nuclear spin-dependent P-odd amplitudes $E1_{SD}$ are in units of $(\kappa e a_0 \times 10^{-11})$, A is the number of nucleons in the nucleus.

Isotope	Transition	$F' \to F$	$E1_{SD}$
$A = 171$	$^1S_0 \to {}^3D_1$	$1/2 \to 1/2$	-2.75
$I = 1/2$	$^1S_0 \to {}^3D_1$	$1/2 \to 3/2$	-1.94
	$^1S_0 \to {}^3D_2$	$1/2 \to 3/2$	9.13
$A = 173$	$^1S_0 \to {}^3D_1$	$5/2 \to 3/2$	2.82
$I = 5/2$	$^1S_0 \to {}^3D_1$	$5/2 \to 5/2$	-0.99
	$^1S_0 \to {}^3D_1$	$5/2 \to 7/2$	-2.85
	$^1S_0 \to {}^3D_2$	$5/2 \to 3/2$	3.89
	$^1S_0 \to {}^3D_2$	$5/2 \to 5/2$	-6.79
	$^1S_0 \to {}^3D_2$	$5/2 \to 7/2$	-8.05

S.G. Porsev et al. Hyperfine Interactions **127,** 395 (2000)

"Best guess" PV difference between ^{173}Yb *F'*=7/2 and F'=3/2 ~ 0.15%

But…partial cancellation due to $V_e A_n$

Need to boost SNR!

Yb sensitivity improvements

Need ~ 10 times better SNR for anapole, neutron skins

- Optical pumping in the spin-isotopes
- Laser cooling of the atomic beam
- Optimization of the oven flux
- Power build-up cavity mirror upgrades

  (increase intracavity power, decrease the intensity)

PV in dysprosium

Atomic PV in Dy

Dysprosium {

- Z=66
- 7 stable isotopes (A=156,158,160-164)
- ^{163}Dy & ^{161}Dy : I=5/2 (anapole moment)

Atomic PV in Dy

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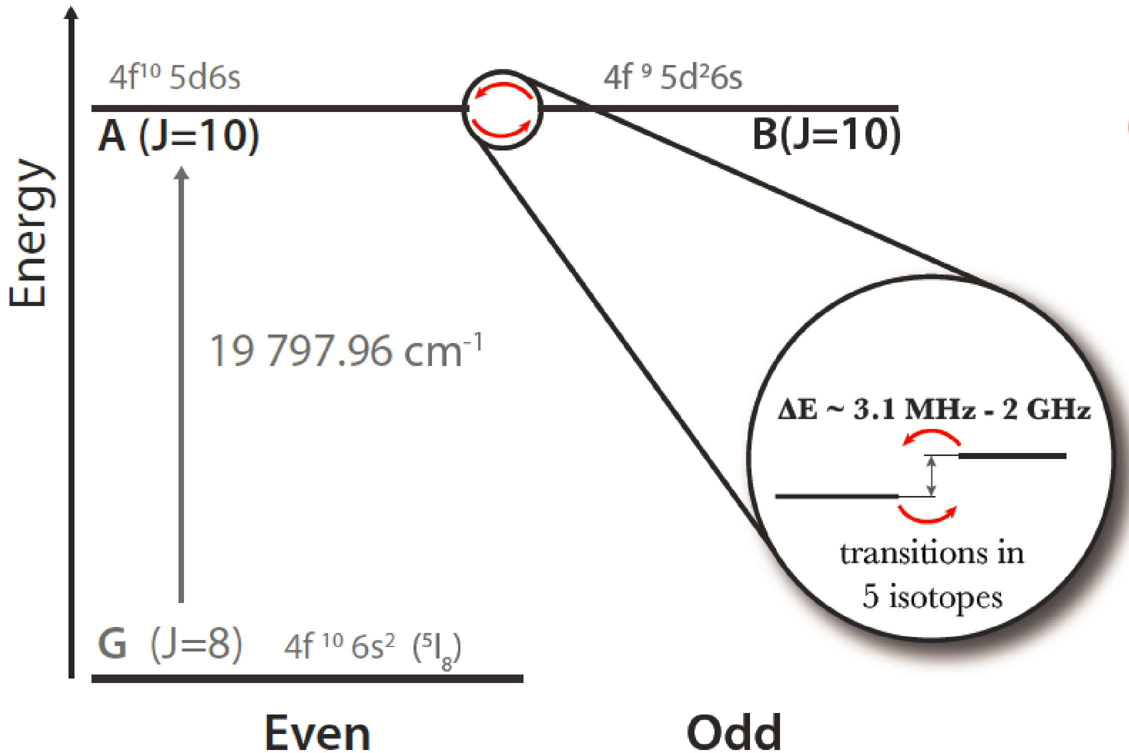

$$\delta_W = \frac{\langle n'p|H_W|ns\rangle}{\Delta E} \sim Z^3$$

Theory (1994)

$|H_W|$=70 ± 40Hz

V.A. Dzuba et al., PRA 50, 3812 (**1994**)

V. A. Dzuba, V. V. Flambaum, and I. B. Khriplovich (1986)
Enhancement of P- & T-odd effects in rear-earth atoms

Dy parity violation experiment becomes…

PHYSICAL REVIEW A VOLUME 56, NUMBER 5 NOVEMBER 1997

Search for parity nonconservation in atomic dysprosium

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[2]*Nuclear Science Division, E. O. Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[3]*Center for Beam Physics, E. O. Lawrence Berkeley National Laboratory, Berkeley, California 94720*

(Received 2 June 1997)

Results of a search for parity nonconservation (PNC) in a pair of nearly degenerate opposite-parity states in atomic dysprosium are reported. The sensitivity to PNC mixing is enhanced in this system by the small energy separation between these levels, which can be crossed by applying an external magnetic field. The metastable odd-parity sublevel of the nearly crossed pair is first populated. A rapidly oscillating electric field is applied to mix this level with its even-parity partner. By observing time-resolved quantum beats between these sublevels, we look for interference between the Stark-induced mixing and the much smaller PNC mixing. To guard against possible systematic effects, reversals of the signs of the electric field, the magnetic field, and the decrossing of the sublevels are employed. We report a value of $|H_w| = |2.3 \pm 2.9\ \text{(statistical)} \pm 0.7\text{(systematic)}|$ Hz for the magnitude of the weak-interaction matrix element. A detailed discussion is given of the apparatus, data analysis, and systematic effects. [S1050-2947(97)02111-2]

PHYSICAL REVIEW A **69**, 022105 (2004)

Towards a sensitive search for variation of the fine-structure constant using radio-frequency $E1$ transitions in atomic dysprosium

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(Received 28 August 2003; published 12 February 2004)

PHYSICAL REVIEW A 69, 022105 (2004)

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Limit on the Temporal Variation of the Fine-Structure Constant Using Atomic Dysprosium

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Investigation of the gravitational-potential dependence of the fine-structure constant using atomic dysprosium

S. J. Ferrell,[1] A. Cingöz,[1] A. Lapierre,[2] A.-T. Nguyen,[3] N. Leefer,[1] D. Budker,[1,4] V. V. Flambaum,[5,6] S. K. Lamoreaux,[7] and J. R. Torgerson[3]

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Transverse laser cooling of a thermal atomic beam of dysprosium

N. Leefer,[1,*] A. Cingöz,[1,†] B. Gerber-Siff,[2] Arijit Sharma,[3] J. R. Torgerson,[4] and D. Budker[1,5,‡]

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Limits on Violations of Lorentz Symmetry and the Einstein Equivalence Principle using Radio-Frequency Spectroscopy of Atomic Dysprosium

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PRL **111**, 060801 (2013) PHYSICAL REVIEW LETTERS week ending 9 AUGUST 2013

New Limits on Variation of the Fine-Structure Constant Using Atomic Dysprosium

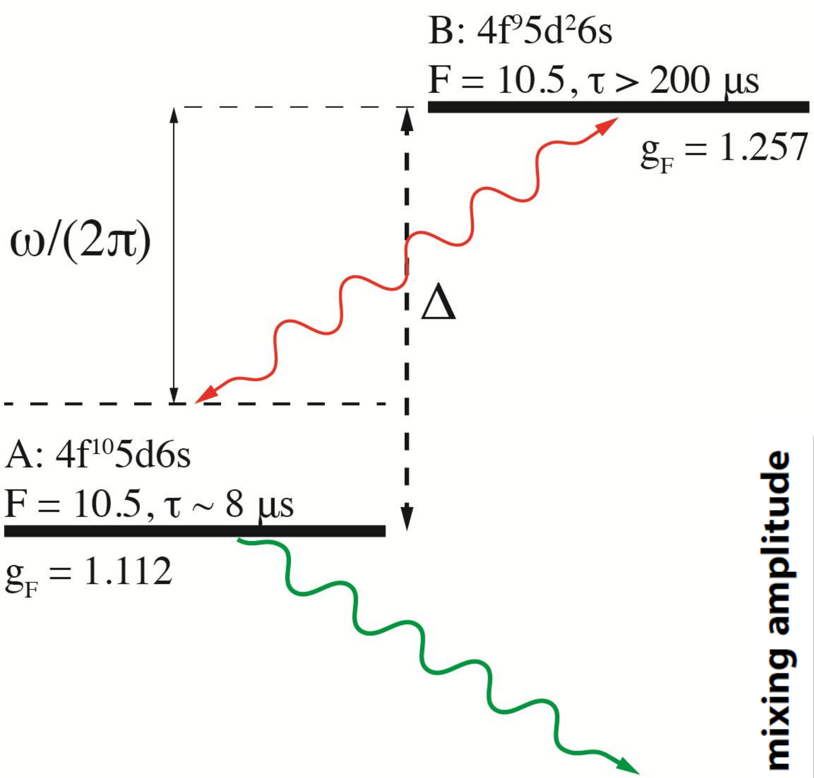
N. Leefer,[1] C. T. M. Weber,[2] A. Cingöz,[3] J. R. Torgerson,[4] and D. Budker[1,5]

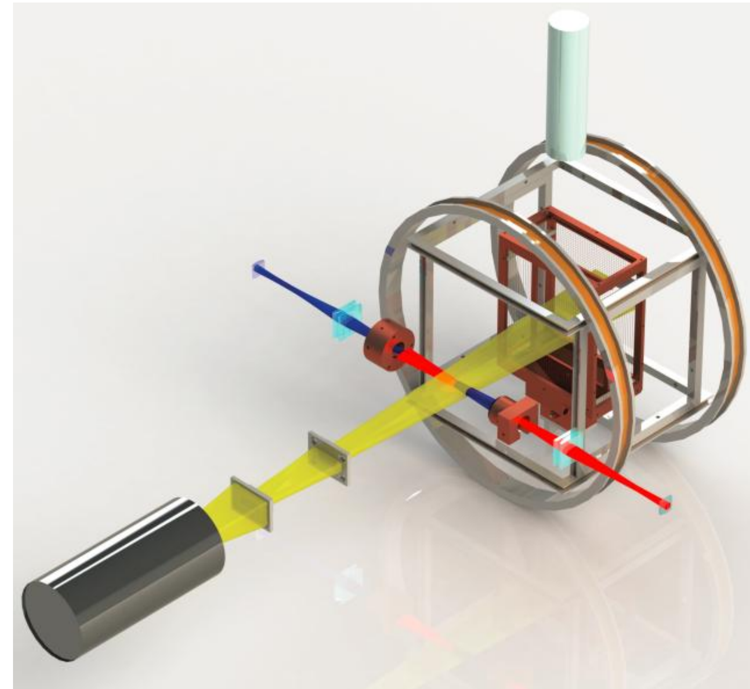
Revived Dy Atomic PV experiment

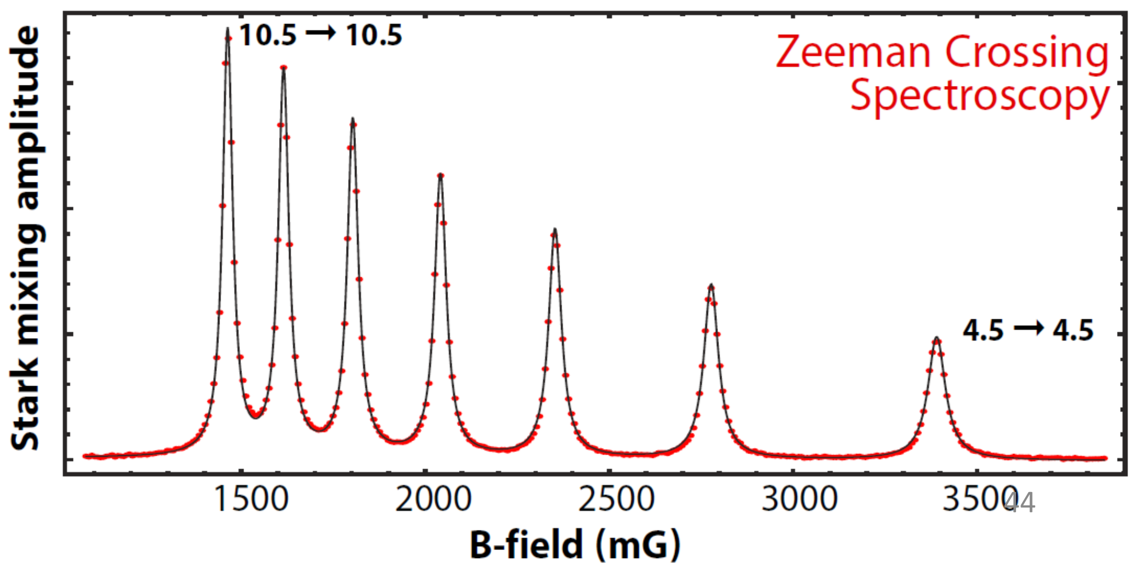
Improved theory (2010)

$|H_W| = 4 \pm 4$ Hz

V. A. Dzuba & V. V. Flambaum,
PRA 81, 052515 (**2010**)





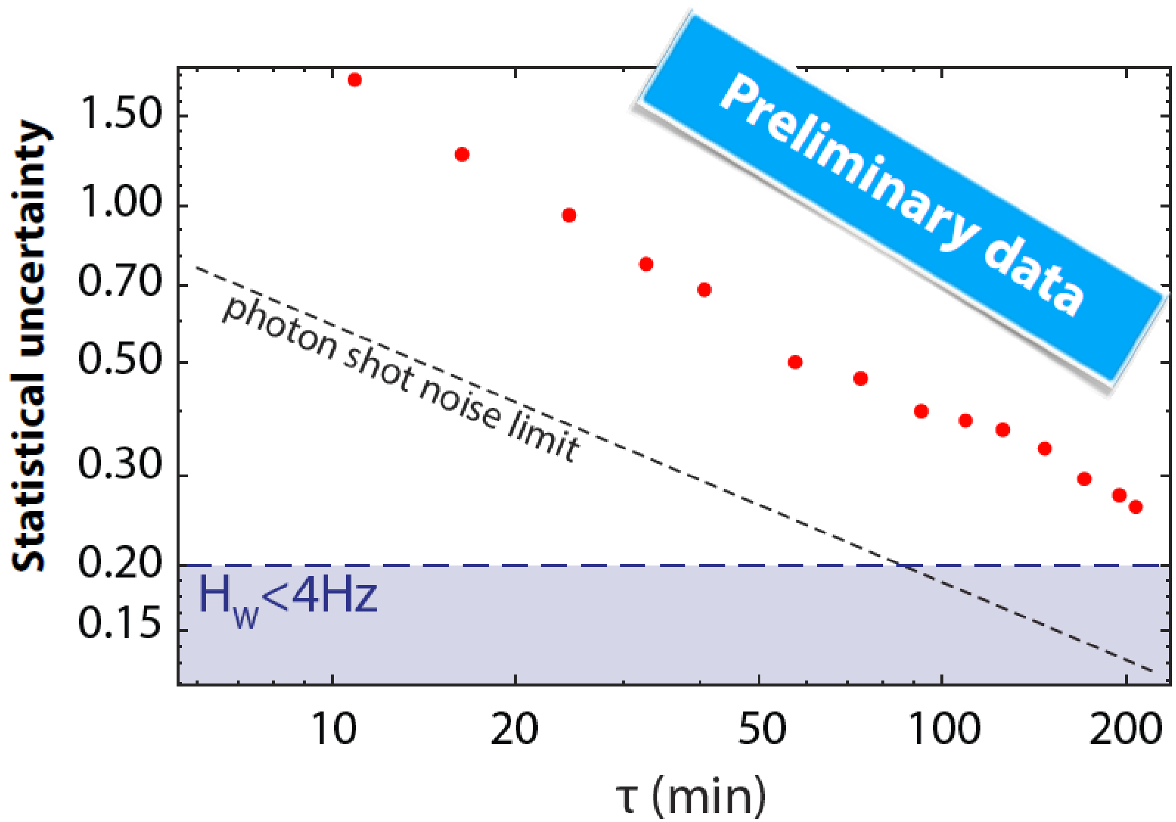


Allowed Stark-PNC interference

$$\dot{E} \cdot (B - Bcrossing)$$

Dy setup upgrades & current status

- New apparatus
- CW laser sources
- Soon: Optical pumping to extreme m_F states (x30 signal increase)

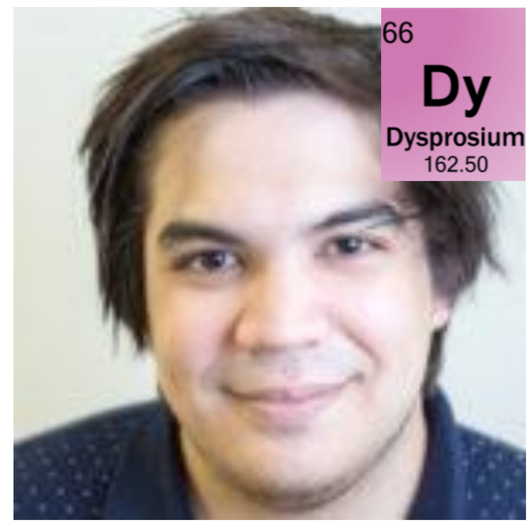


Dr. L. Bougas

Dr. A. Sharma

Prof. D. Budker

A. Frabricant



P. Leyser

Backup slides

Atomic PV landmarks

- 1959 **Ya. B. Zel'dovich:**

PNC (Neutr. Current) → Opt. Rotation in atoms

- 1974 **M.-A. & C. Bouchiat**

Z^3 enhancement → PV observable in **heavy** atoms

- 1978-9 **Novosibirsk, Berkeley**

discovery of PV in OR(**Bi**) and Stark-interf.(**Tl**)

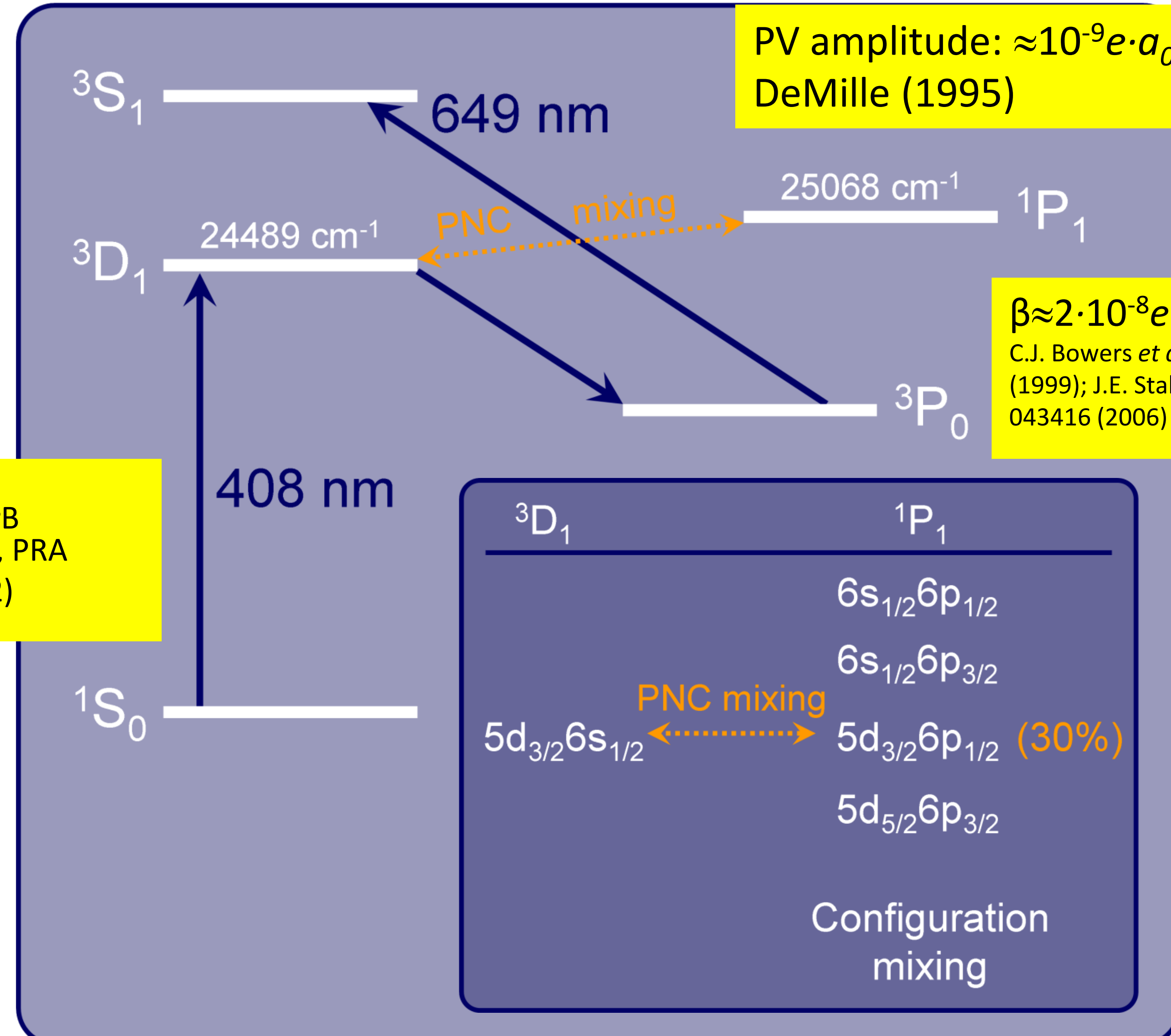
- …1995 **Boulder, Oxford, Seattle, Paris**

PV measured to 1-2% in Cs, Tl, Bi, Pb

- 1997 **Boulder** 0.35% measurement, discovery of anapole moment
- 2009 Berkeley, 10% measurement in Yb. Largest effect ever observed in any atom

The Yb PV Experiment

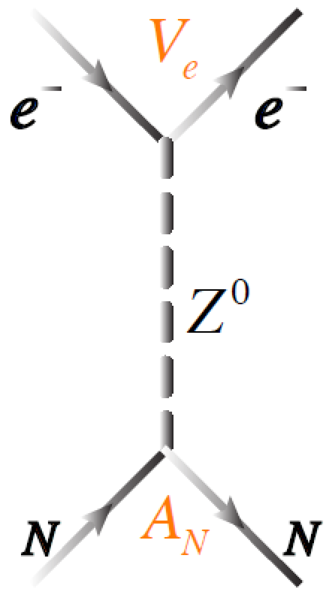
PV amplitude: $\approx 10^{-9} e \cdot a_0$
DeMille (1995)



$\beta \approx 2 \cdot 10^{-8} e a_0 / (\text{V/cm})$
C.J. Bowers *et al*, PRA **59**(5), 3513 (1999); J.E. Stalnaker et al, PRA **73**, 043416 (2006)

$|M1| \approx 10^{-4} \mu_B$
J.E. Stalnaker, *et al*, PRA **66**(3), 31403 (2002)

Nuclear spin-dependent APV: $V_e \cdot A_N$



Only valence nucleon contributes

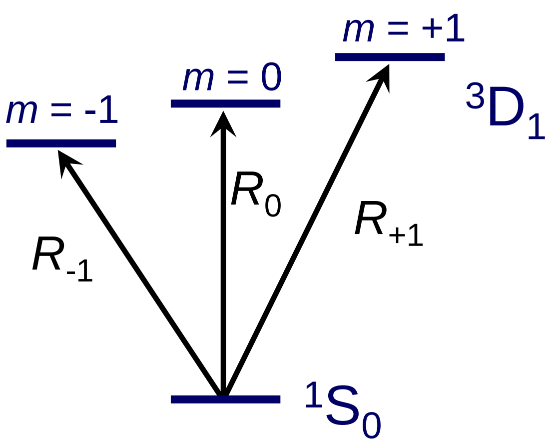
Suppressed by ~ 10^3 compared to NSI effect

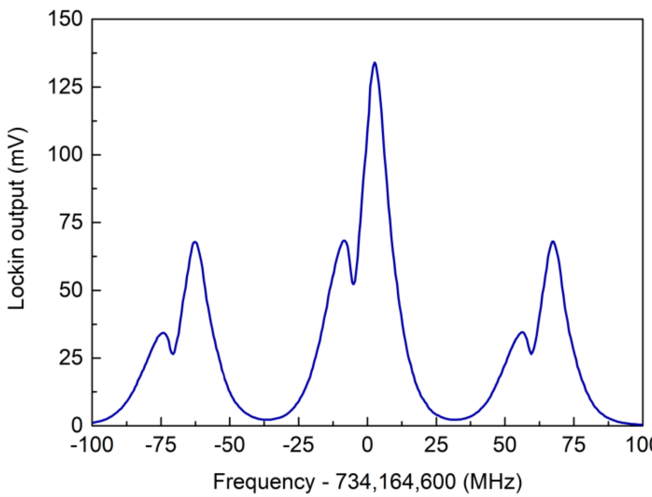
$$H_{axial} = \frac{G_F}{\sqrt{2}} \eta_{axial} (\boldsymbol{\alpha} \cdot \boldsymbol{I}) \rho(r)$$

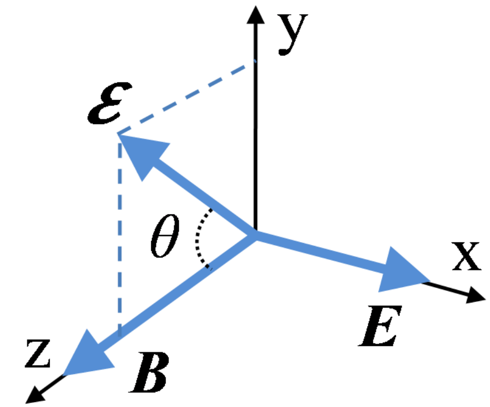
$$\eta_{axial} = -C_N^{(2)} \frac{\kappa_N - 1/2}{I(I+1)}$$

N=*p* or *n*

The Yb PV experiment







Rotational invariant:

$$\left(\vec{\varepsilon}\cdot\vec{B}\right)\left(\vec{E}\times\vec{\varepsilon}\cdot\vec{B}\right)$$

$$R_0 \propto \left|A_{Stark}+A_{PNC}\right|^2 \approx \beta^2 E^2 \sin^2\theta + \boxed{2E\beta\zeta\cos\theta\sin\theta}$$

Stark-PV interference

1) Modulate the E-field: $E=E_{dc}+E_0\cos\omega t$ & look at 1st to 2nd harmonics ratio:

$$r = \frac{4E_{dc}}{E_0}+\frac{4\zeta}{\beta E}\cot\theta$$

2) Reverse θ (π/4 ⇔ - π/4) and look at difference in ratio:

$$r_+ - r_- = \frac{8\zeta}{\beta E}$$

3) Average over opposite E_{dc} and B.

PV asymmetry: $4\zeta/\beta E_0 \approx 10^{-4}$

Yb systematics studies

Preliminary studies (~ 1 year)

- Check model

$$r_0 = \frac{4E_{dc}}{E_0} + \boxed{\frac{4\zeta}{\beta E_0}\cot\theta} + \frac{4b_x e_y}{BE_0}\cot\theta - \frac{4b_x e_z}{BE_0} + \text{....???}$$

- Check that PV result does not change with things like:
  - Varying E, B amplitude and E frequency.
  - Varying θ.
  - Different field plates and HV amplifiers.
  - Acqusition without power-build-up cavity .
  - Varying position on lineshape.
  - With left or right half of atom beam blocked.
- Measure "zero": asymmetry on ^{171}Yb F=1/2→ F'=1/2 transition.
- Measure PV on m=± 1 components (asymmetry flips sign).
- Calibrations applied to data (polarization θ, transition saturation…)

During the long PV run

- Measure and minimize field imperfections introducing false PV signals
- Monitor calibration parameters.