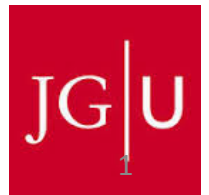


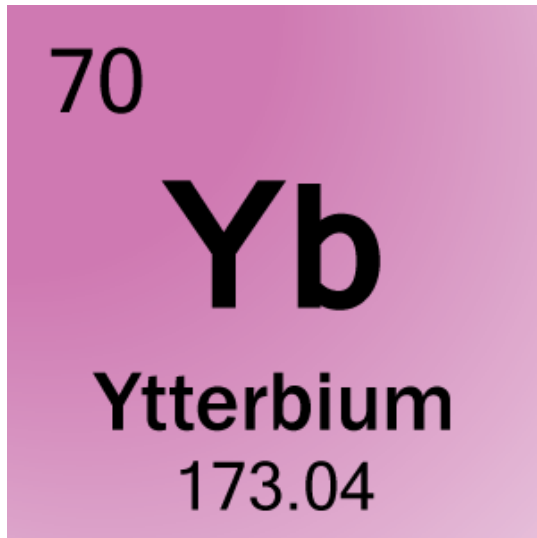
Parity violation in Yb and Dy

Dionysis Antypas

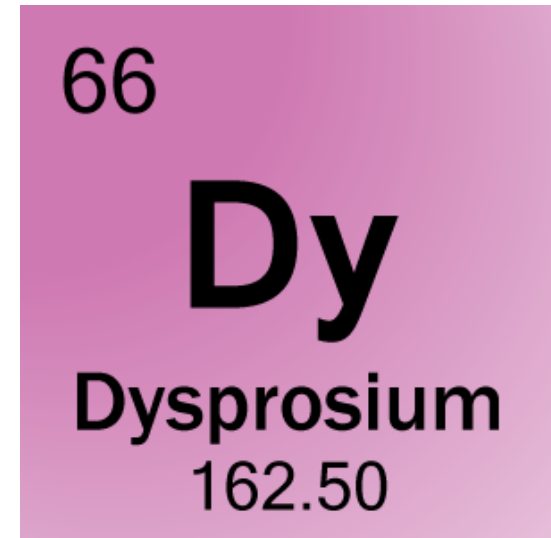
PVES 2018



Atomic Parity Violation at the Helmholtz- Institut Mainz



Dionysis Antypas
Anne Fabricant

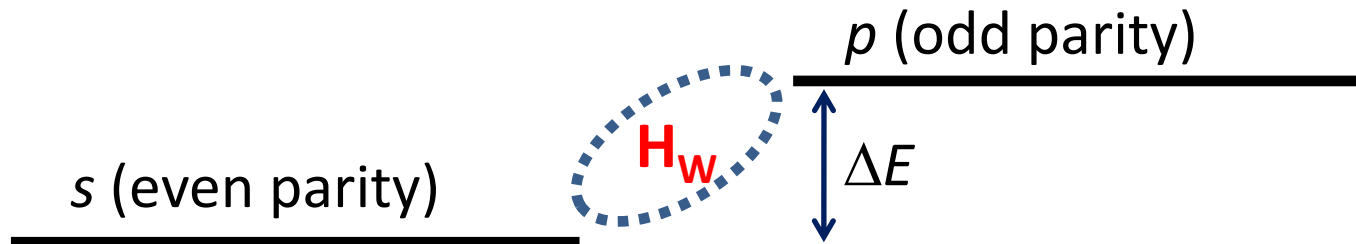


Arijit Sharma
Lykourgos Bougas
Peter Leyser

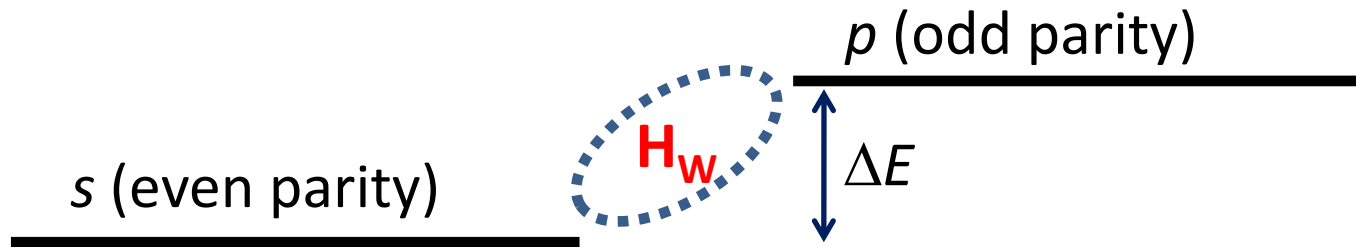
Outline

- 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)



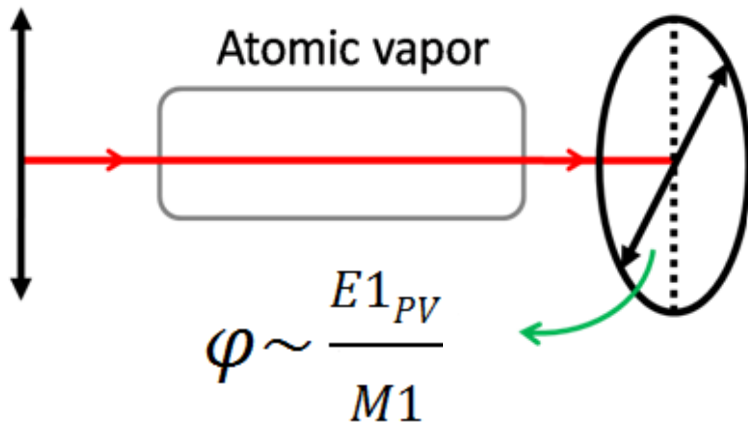
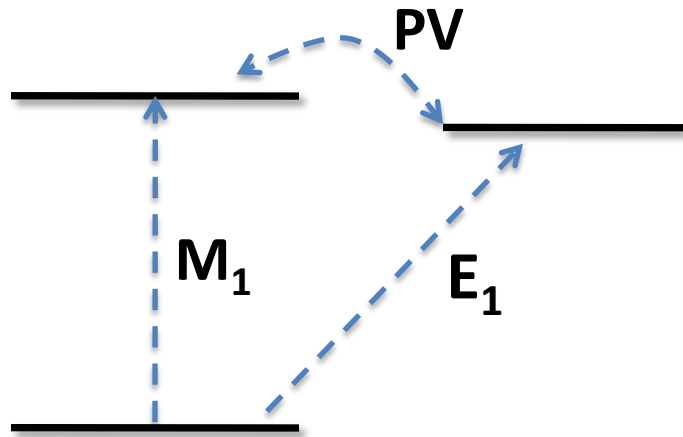
$$s \rightarrow s + i\varepsilon p; p \rightarrow p + i\varepsilon s$$

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

Atomic PV **Enhancement:**

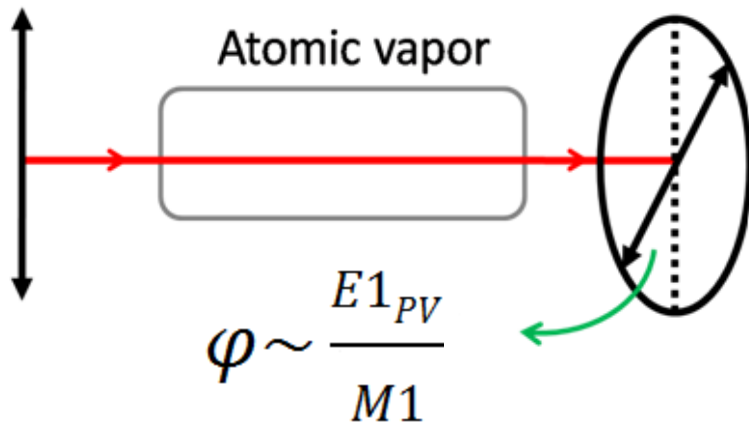
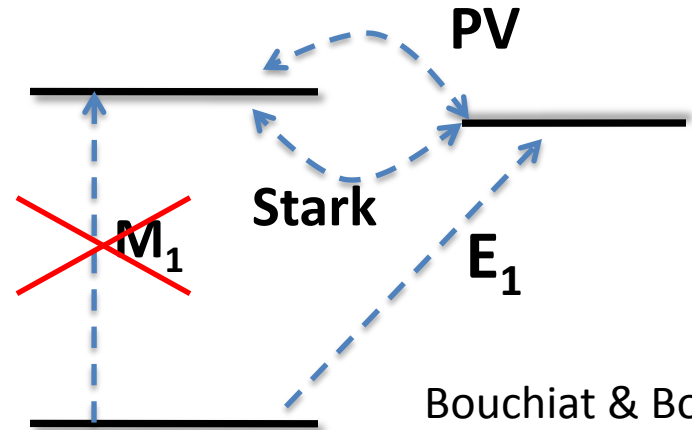
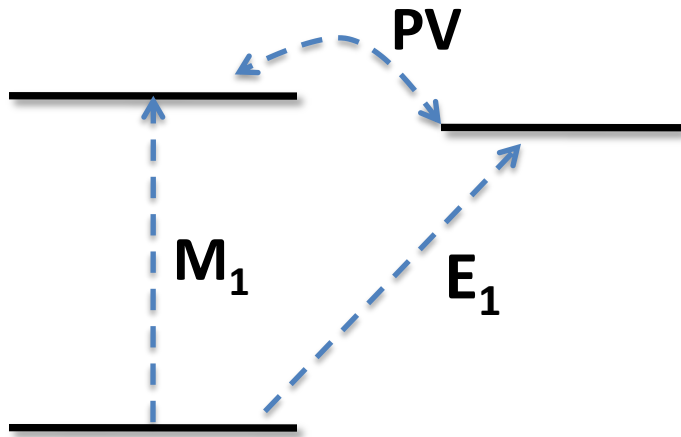
- Heavy atoms (high Z)
- Small ΔE

Types of atomic PV experiments



- 100% contrast (small signal)
- No reversals

Types of atomic PV experiments



- 100% contrast (small signal)
- No reversals

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

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

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

- Small contrast on large signal
- Many reversals for systematics

Experimental atomic PV studies

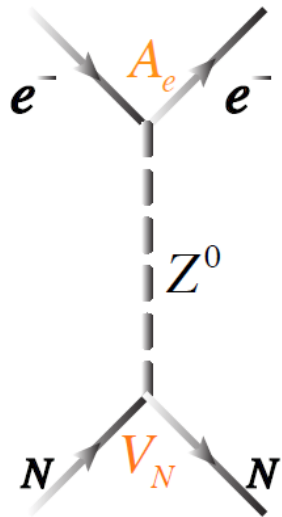
The image shows a periodic table of elements. Red boxes highlight the following elements: Cesium (Cs), Barium (Ba), Francium (Fr), Radium (Ra), Thallium (Tl), Lead (Pb), Bismuth (Bi), Samarium (Sm), Dysprosium (Dy), and Ytterbium (Yb). The periodic table includes element symbols, names, and atomic numbers. The highlighted elements are: Cs (55), Ba (56), Fr (87), Ra (88), Tl (81), Pb (82), Bi (83), Sm (62), Dy (66), and Yb (70).

1 IA 11A																	18 VIIIA 8A
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.933	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.09	35 Br Bromine 79.904	36 Kr Krypton 84.80
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium [223.028]	88 Ra Radium [226.025]	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown
Lanthanide Series		57 La Lanthanum 138.906	58 Ce Cerium 140.115	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.966	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967	
Actinide Series		89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]	

...and a molecule: BaF

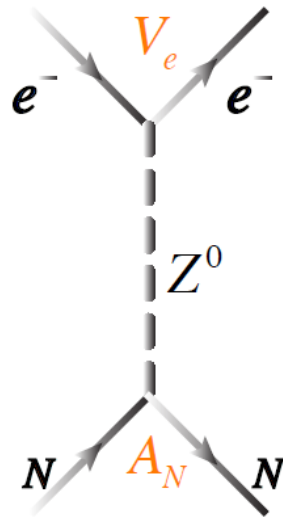
Atomic parity violation: Main processes

Nuclear-spin Independent (NSI)

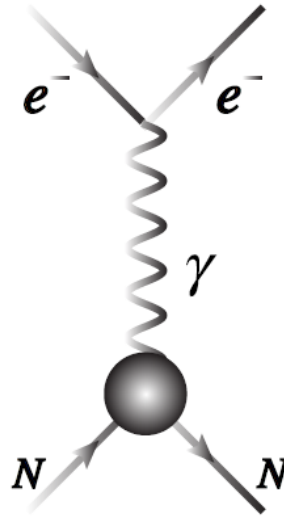


Weak neutral currents

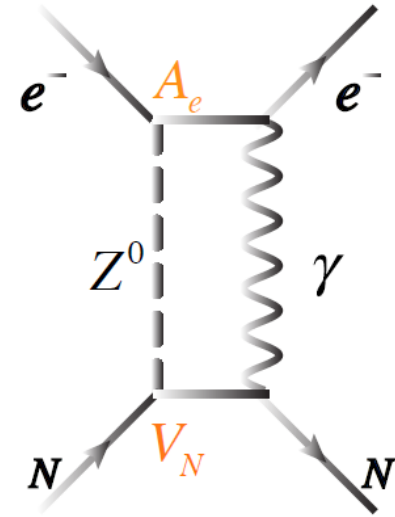
Nuclear-spin dependent (NSD)



Weak neutral currents



Anapole moment-hadronic PV



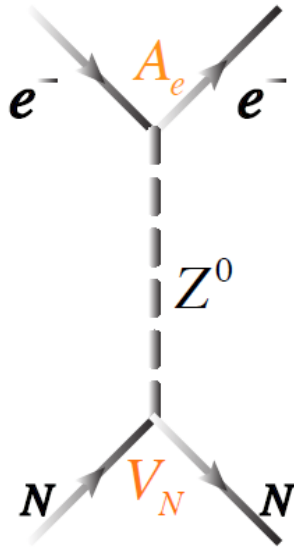
Hyperfine corrections to weak neutral currents

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

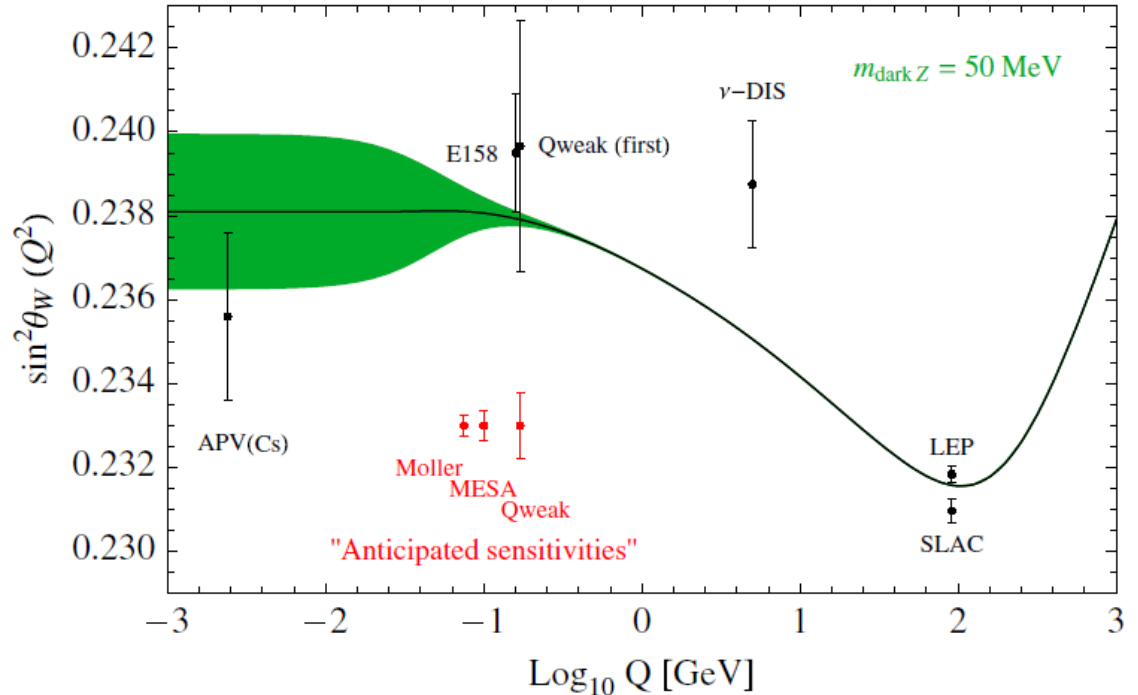
$$H_{NSD} = \frac{G_F}{\sqrt{2}} (\eta_{axial} + \eta_{AM} + \eta_{hf}) (\boldsymbol{\alpha} \cdot \mathbf{I}) \rho(r)$$

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

Nuclear spin-independent atomic PV



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

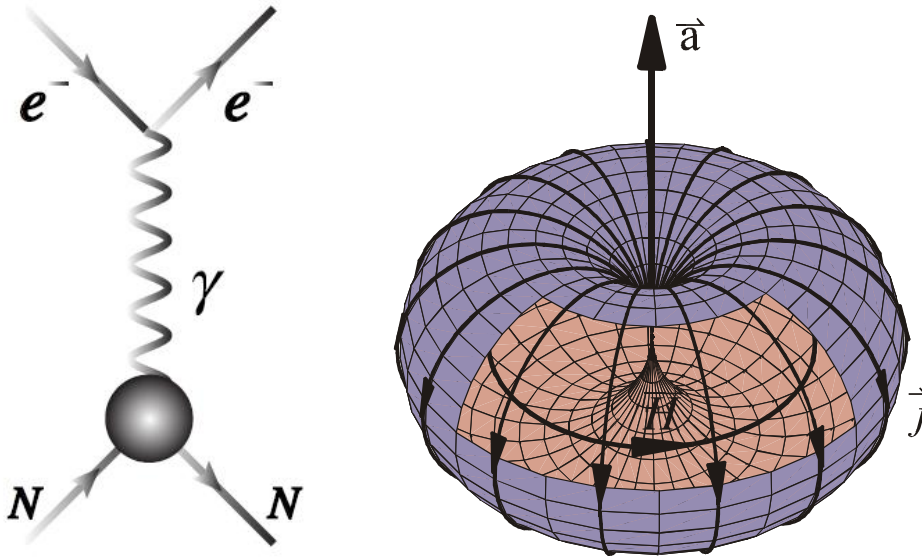


Davoudiasl et al, Phys. Rev. D 89, 1402.3620

- 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)

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

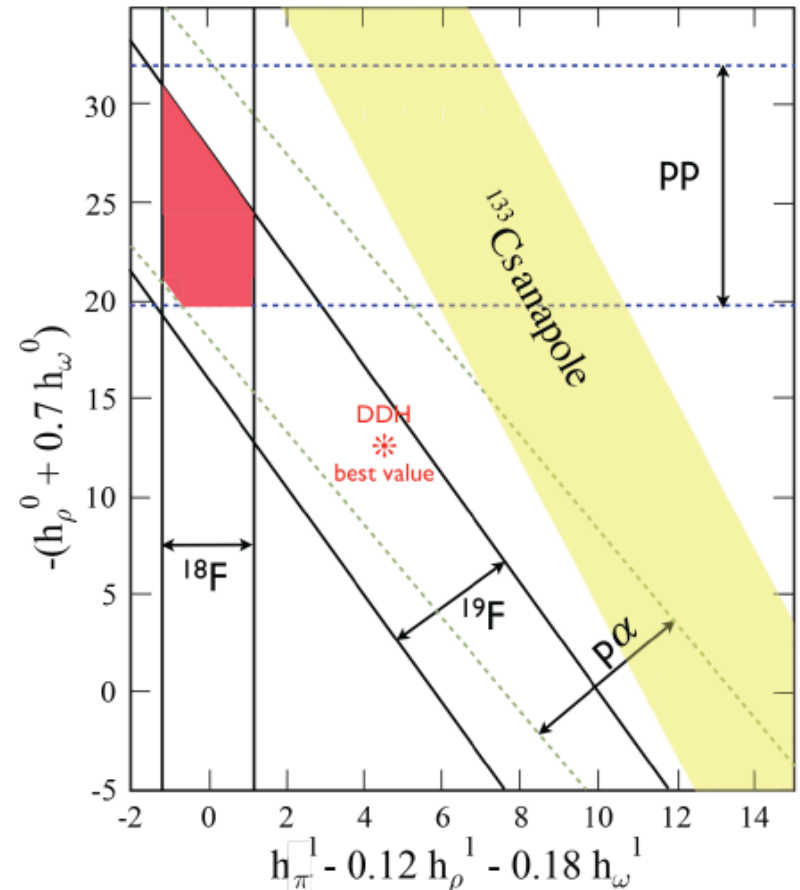
Nuclear spin-dependent atomic PV: Anapole



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

Anapole:

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

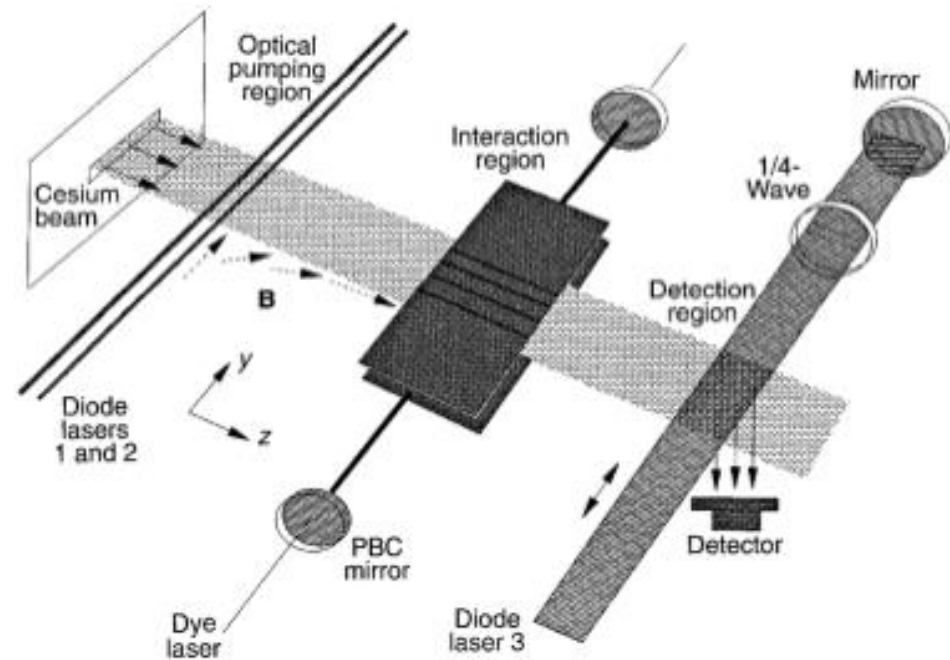
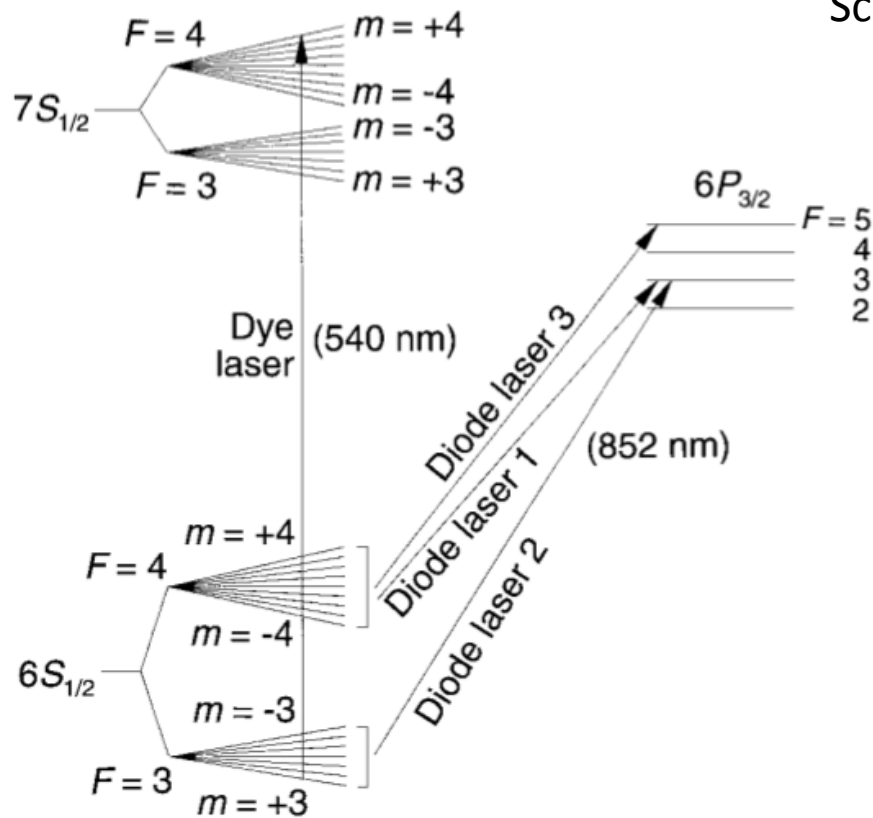


Safranova et al. arXiv:1710.01833

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

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

Atomic structure calculations

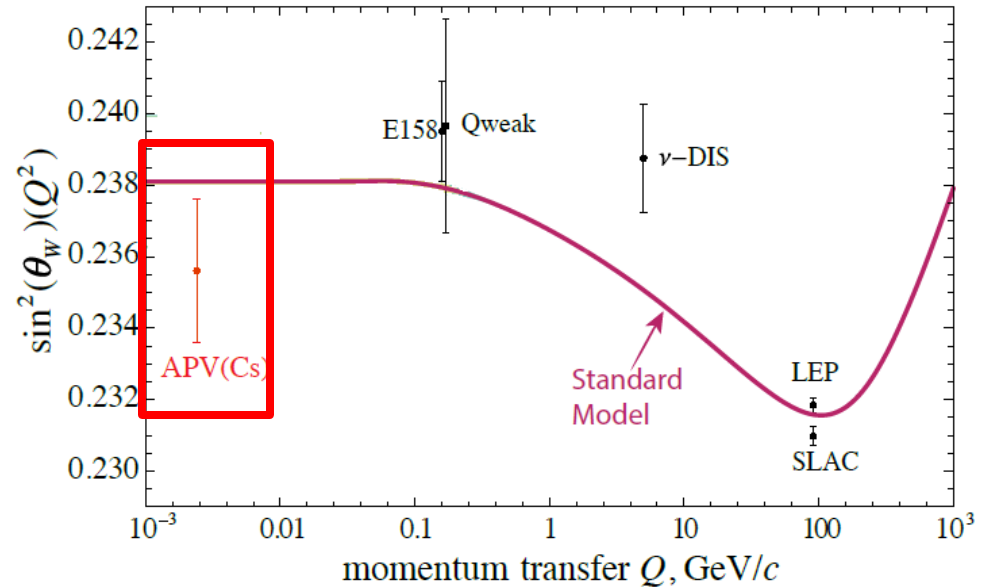
$$E1_{\text{PNC}} = 0.8977(40) \times 10^{-11} i(-Q_W/N)$$

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

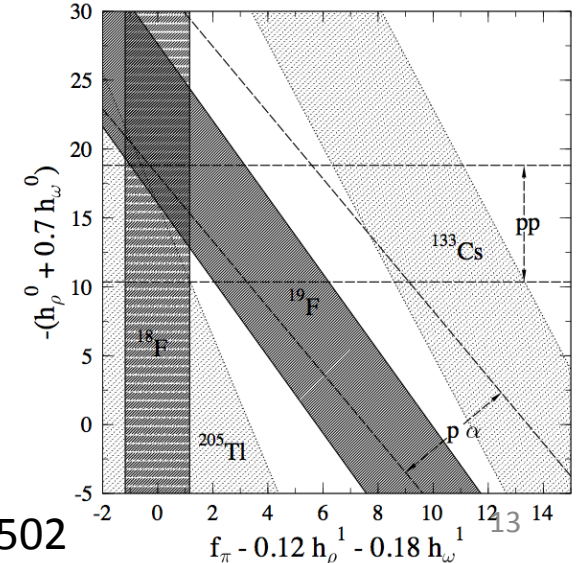
$$Q_W = -N + Z \cdot (1 - 4 \sin^2 \vartheta_W) + \Delta Q_{\text{New Physics}}$$

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

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



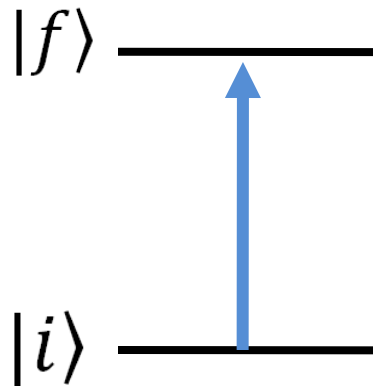
Davoudiasl et al,
Phys. Rev. D 89,
1402.3620



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

Isotopic ratios in atomic PV

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

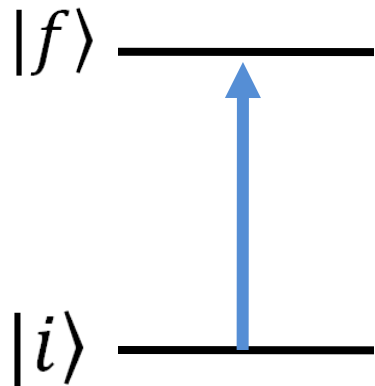


$$E1_{PV} = \langle f | D | i \rangle$$

Element	δk_{PV}
Cs	0.4 %
Yb	10 %

Isotopic ratios in atomic PV

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

Element	δk_{PV}
Cs	0.4 %
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➤ 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)

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

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- Atomic PV \leftrightarrow Neutron distributions

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

skin contribution for ^{170}Yb - ^{176}Yb isotopes $\sim 0.1\%$

Isotopic ratios and neutron skins

[PHYSICAL REVIEW C 79, 035501 (2009)]

Dispelling the curse of the neutron skin in atomic parity violation

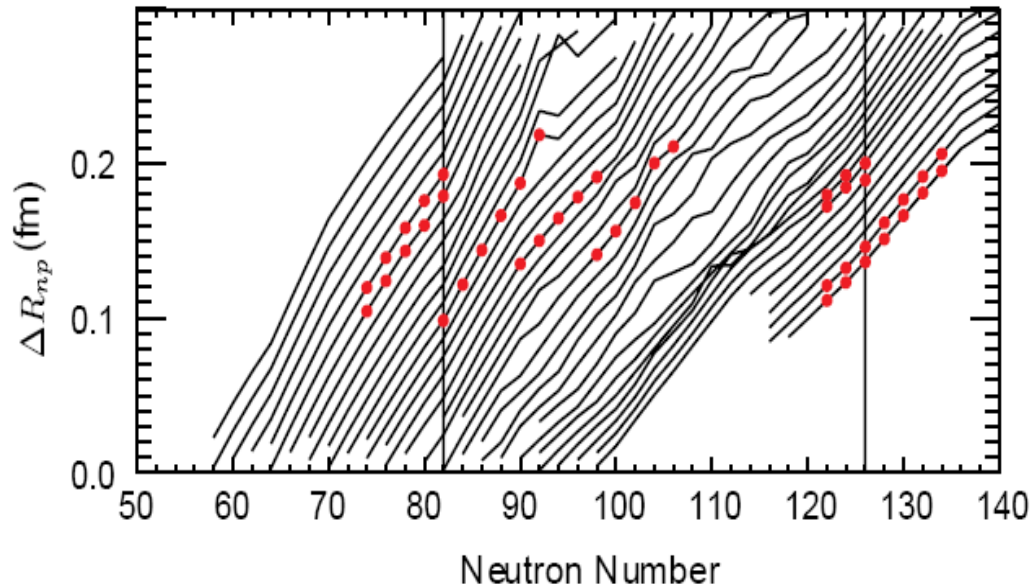
B. A. Brown,¹ A. Derevianko,^{2,3} and V. V. Flambaum³

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

PV in ytterbium

- **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

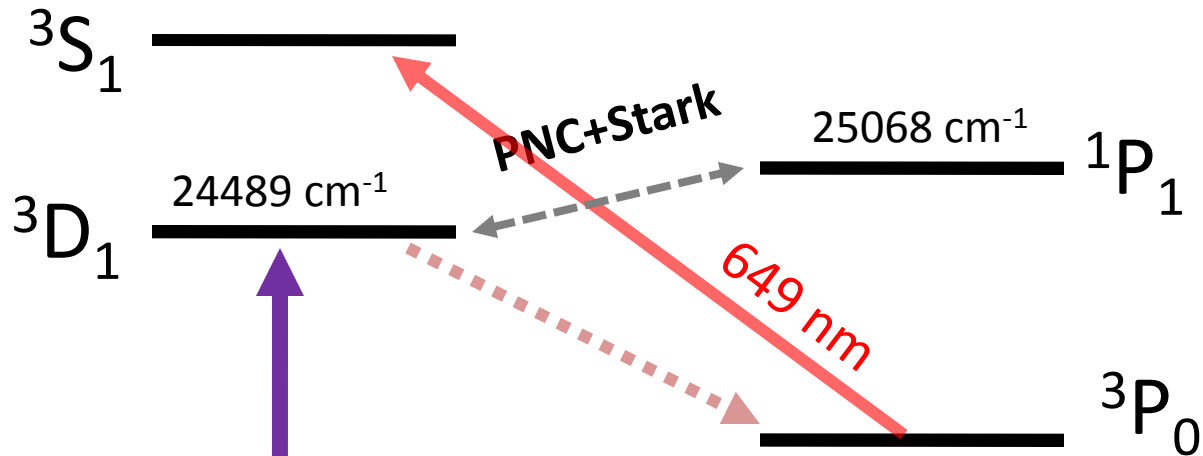
PV in ytterbium

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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

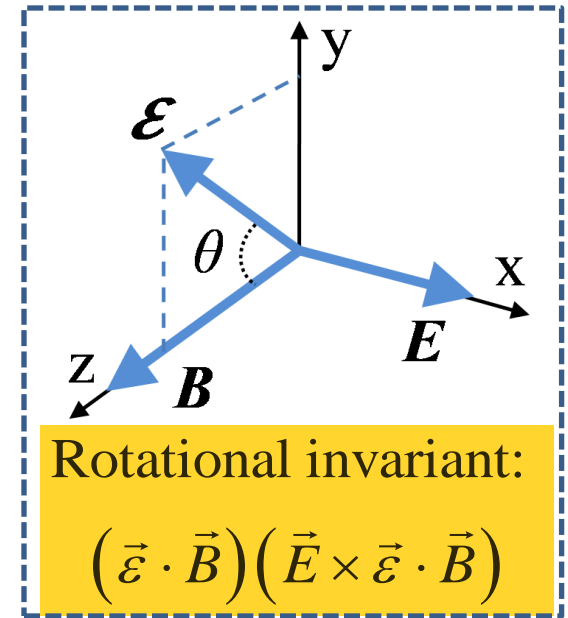
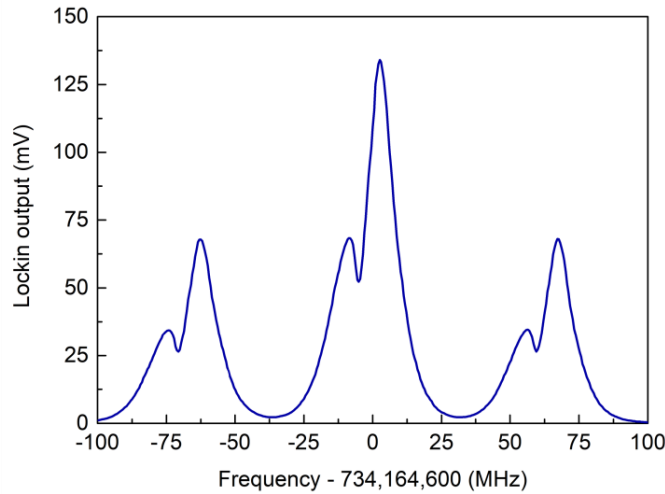
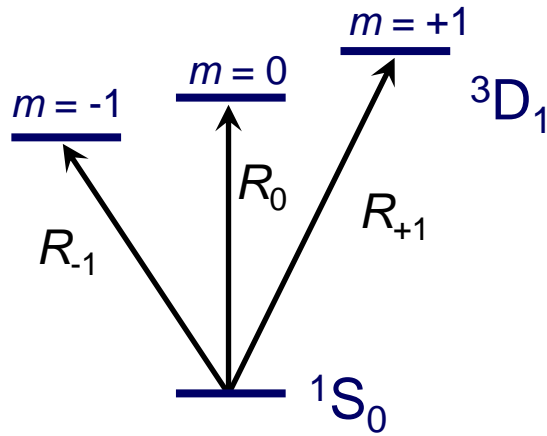


408 nm

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

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

The Yb PV experiment



Rotational invariant:

$$(\vec{\epsilon} \cdot \vec{B})(\vec{E} \times \vec{\epsilon} \cdot \vec{B})$$

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

Stark-PV interference

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

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

^{174}Yb PV results at UC Berkeley

PRL 103, 071601 (2009)

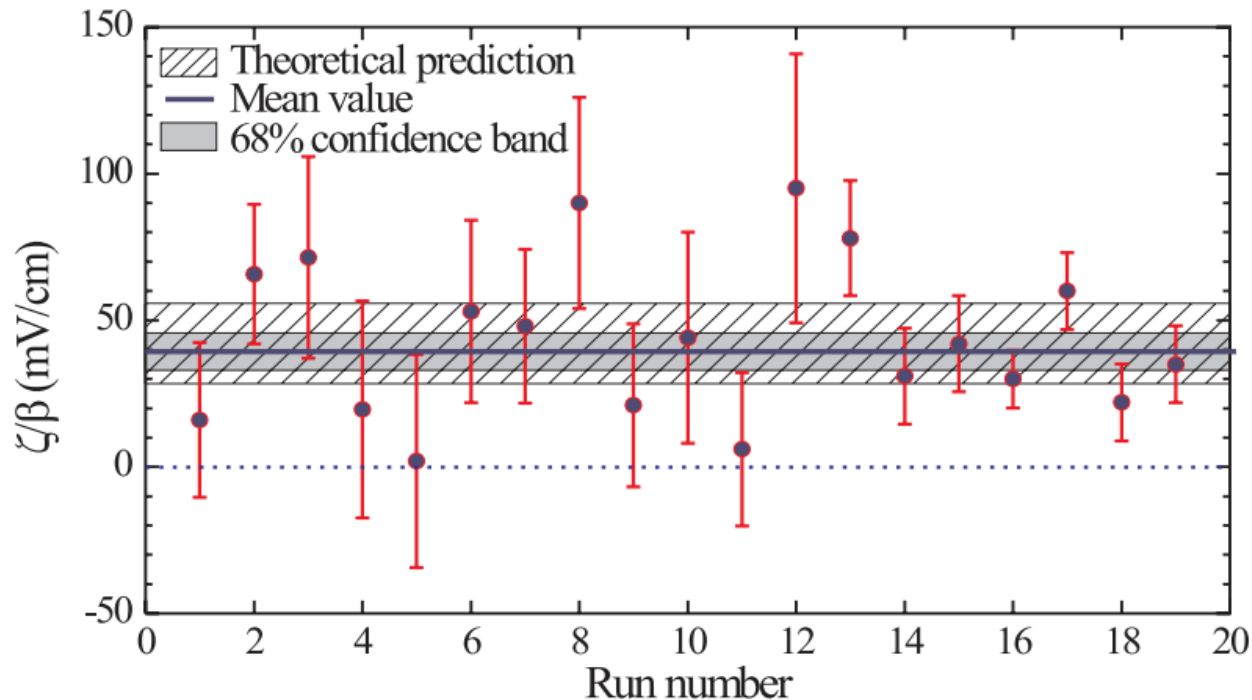
Selected for a **Viewpoint** in *Physics*
PHYSICAL REVIEW LETTERS

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}

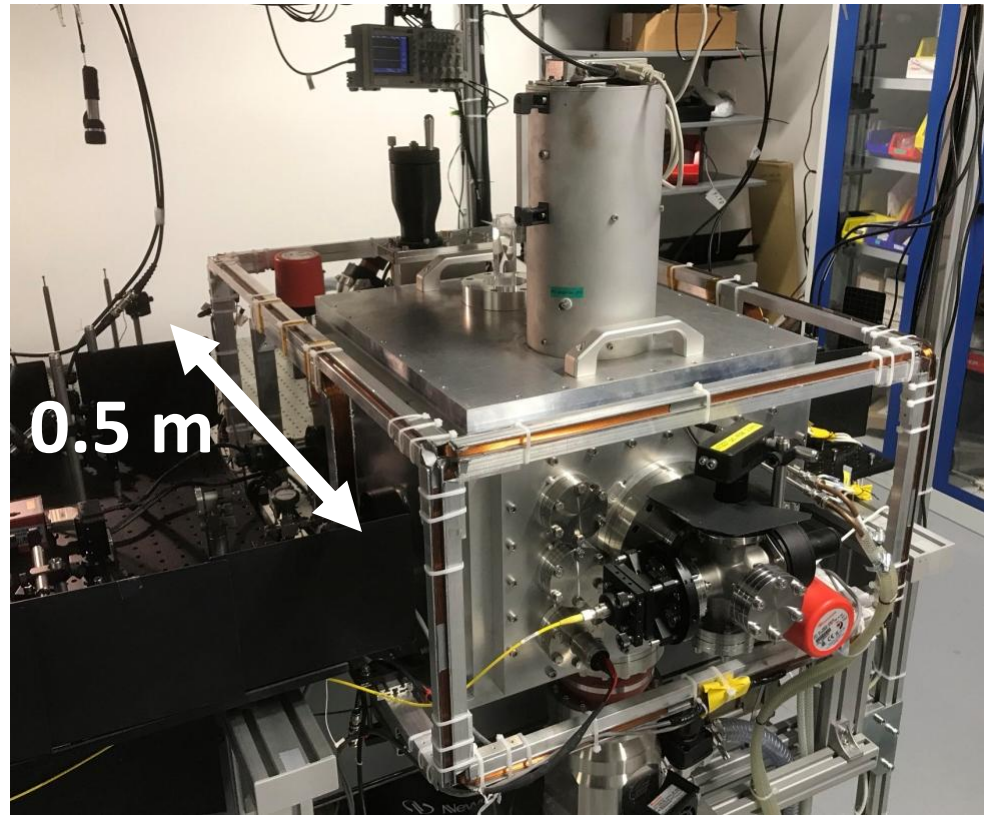


Mean value: $39(4)_{\text{stat}}(5)_{\text{syst}}$ mV/cm, $|\zeta| = 8.7 \pm 1.4 \times 10^{-10} e a_0$

Yb reincarnation in Mainz

New apparatus

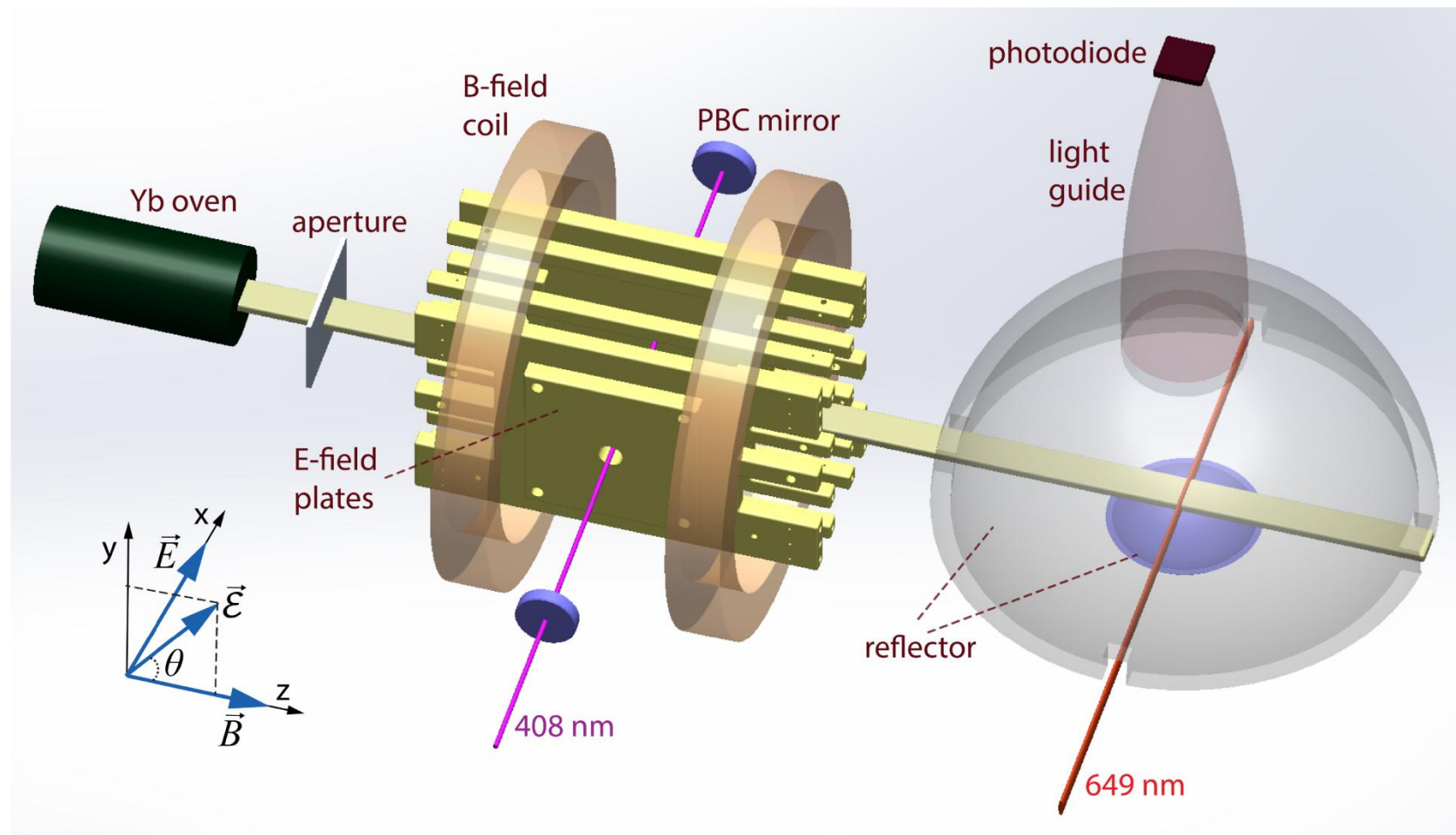
- Newly built vacuum system
- More powerful and frequency stable laser system
- More precise control of fields applied in interaction region
- 20 times better SNR



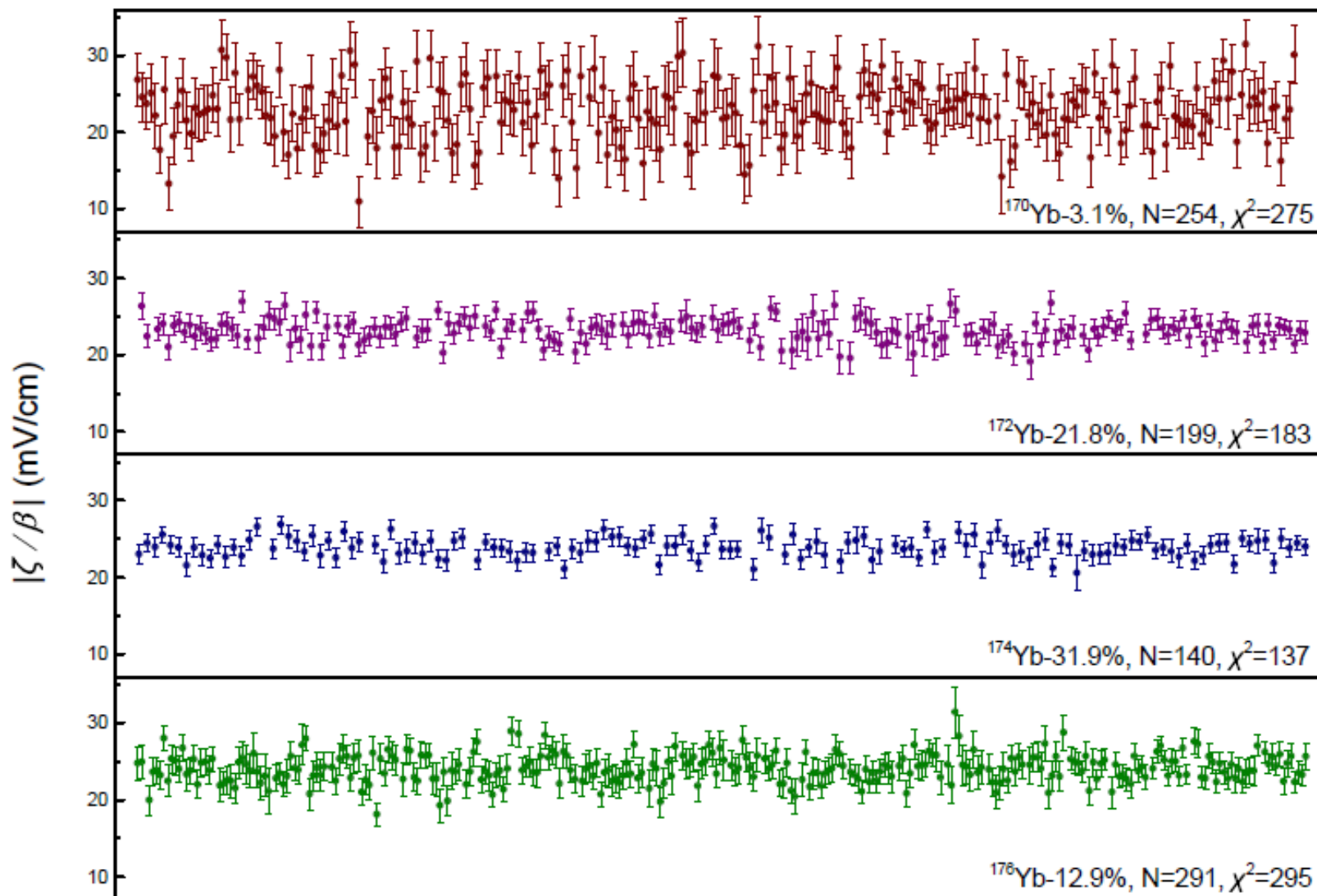
Mainz Roadmap

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

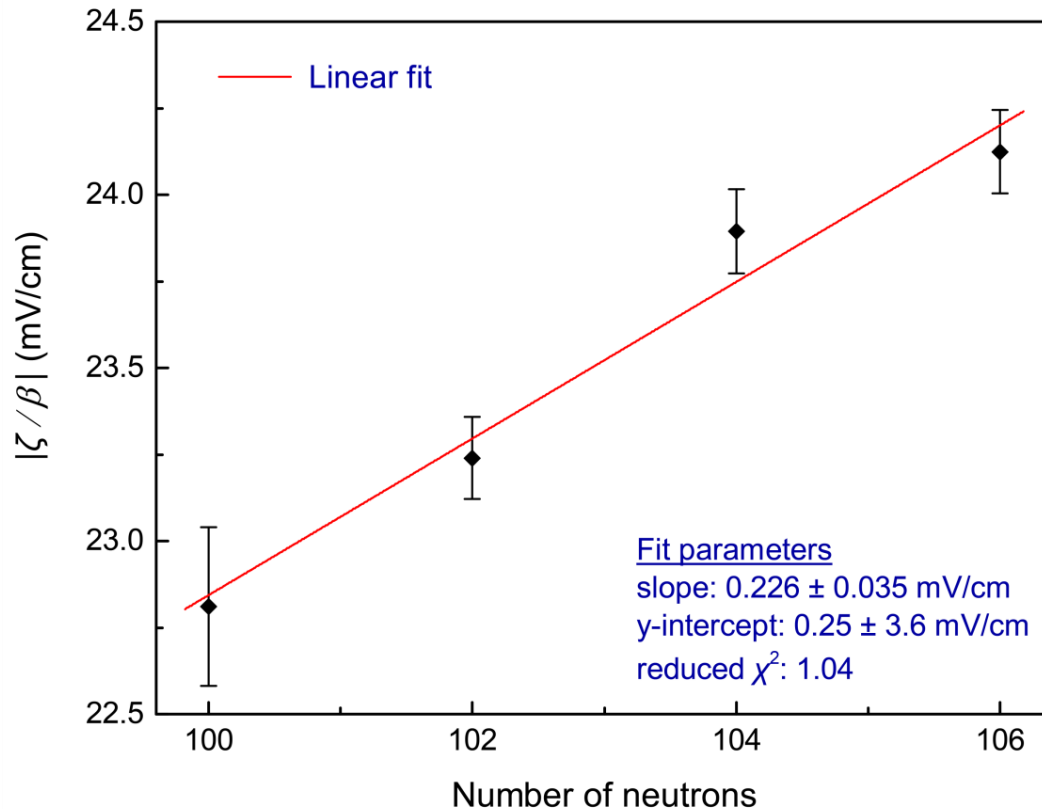
Yb atomic beam apparatus



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](https://arxiv.org/abs/1804.05747)

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

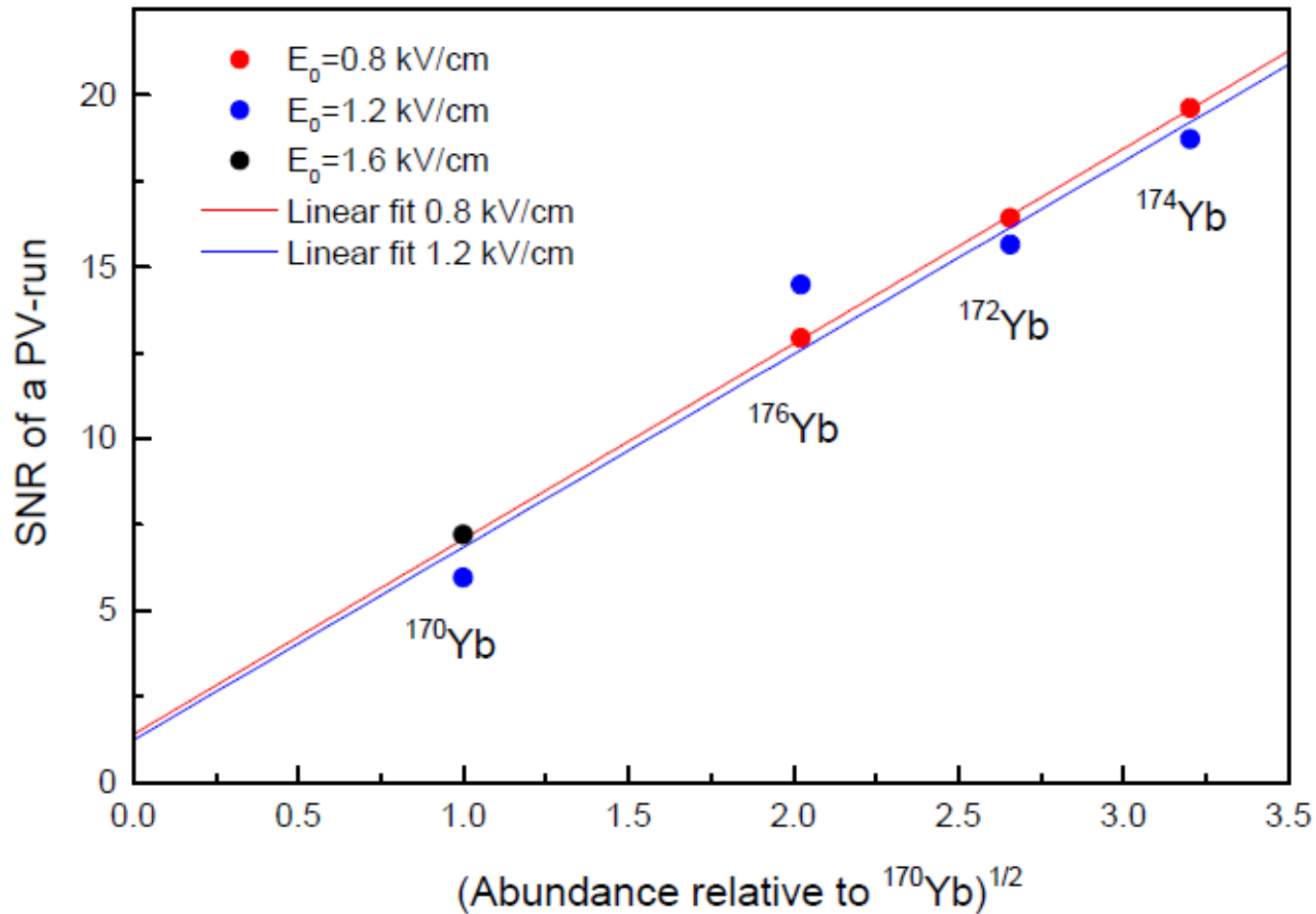
Observation: 0.96(15) % change per neutron

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
False-PV related (1 year of work) → 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)

Isotopic comparison bonus:
decreased sensitivity to systematics

Yb PV measurement sensitivity



Next: spin-dependent PV with Yb

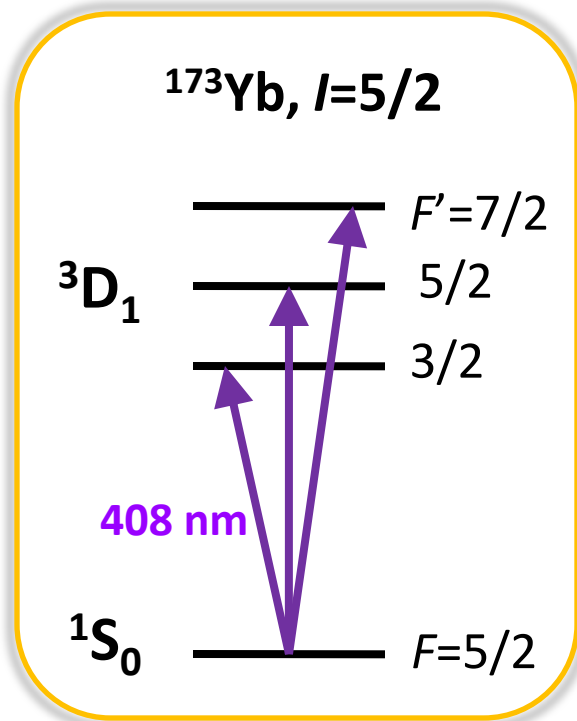


Table 1
Nuclear spin-dependent P-odd amplitudes $E1_{SD}$ are in units of $(\kappa e a_0 \times 10^{-11})$, A is the number of nucleons in the nucleus.

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

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

“Best guess” PV difference between ^{173}Yb $F'=7/2$ and $F'=3/2 \sim 0.15\%$

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)

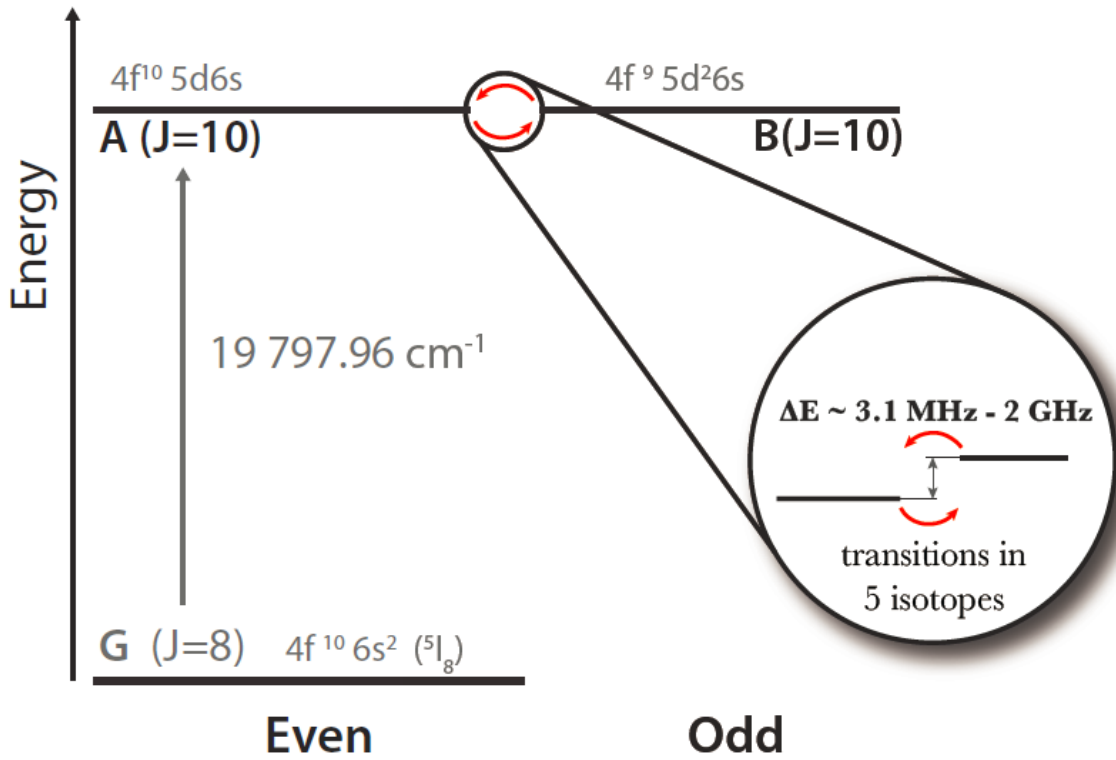
PV in dysprosium

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

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



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

Theory (1994)

$$|H_W| = 70 \pm 40\text{ Hz}$$

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...

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Search for parity nonconservation in atomic dysprosium

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(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]

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

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

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(Received 28 August 2003; published 12 February 2004)

PHYSICAL REVIEW A **76**, 062104 (2007)**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. Torgerson³

PHYSICAL REVIEW A **76**, 062104 (2007)

PHYSICAL REVIEW A **81**, 043427 (2010)

Transverse laser cooling of a thermal atomic beam of dysprosium

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PHYSICAL REVIEW A **76**, 062104 (2007)PHYSICAL REVIEW A **81**, 043427 (2010)

Transverse laser cooling of a thermal atomic beam of dysprosium



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

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PHYSICAL REVIEW A **76**, 062104 (2007)PHYSICAL REVIEW A **81**, 043427 (2010)

Transverse laser cooling of a thermal atomic beam of dysprosium



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



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

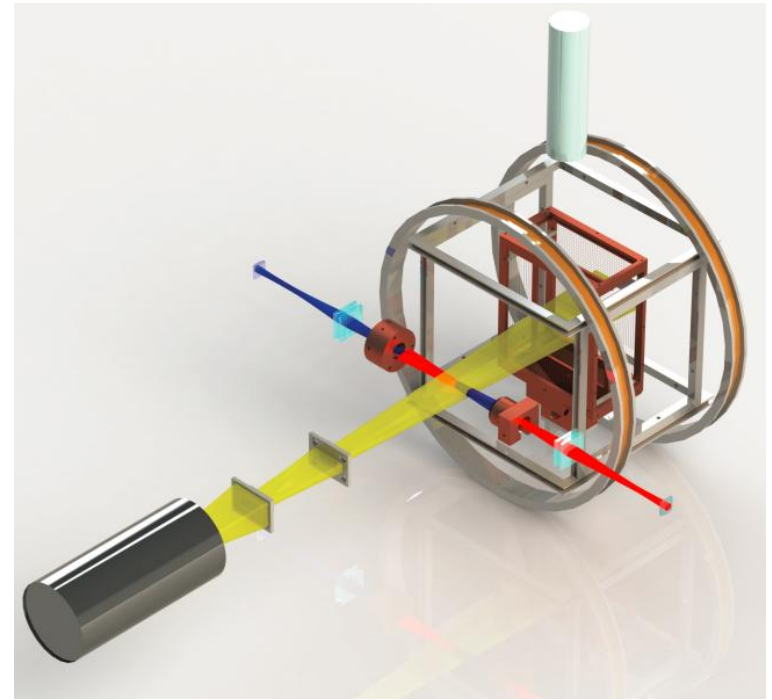
N. Leefler,¹ C. T. M. Weber,² A. Cingöz,³ J. R. Torgerson,⁴ and D. Budker^{1,5}

Revived Dy Atomic PV experiment

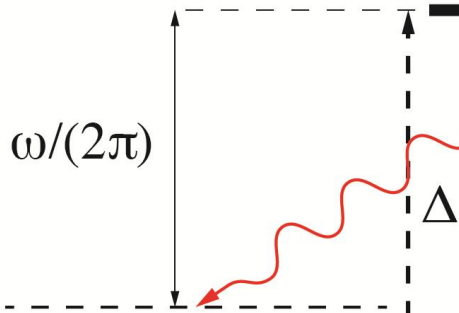
Improved theory (2010)

$$|H_W| = 4 \pm 4 \text{ Hz}$$

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



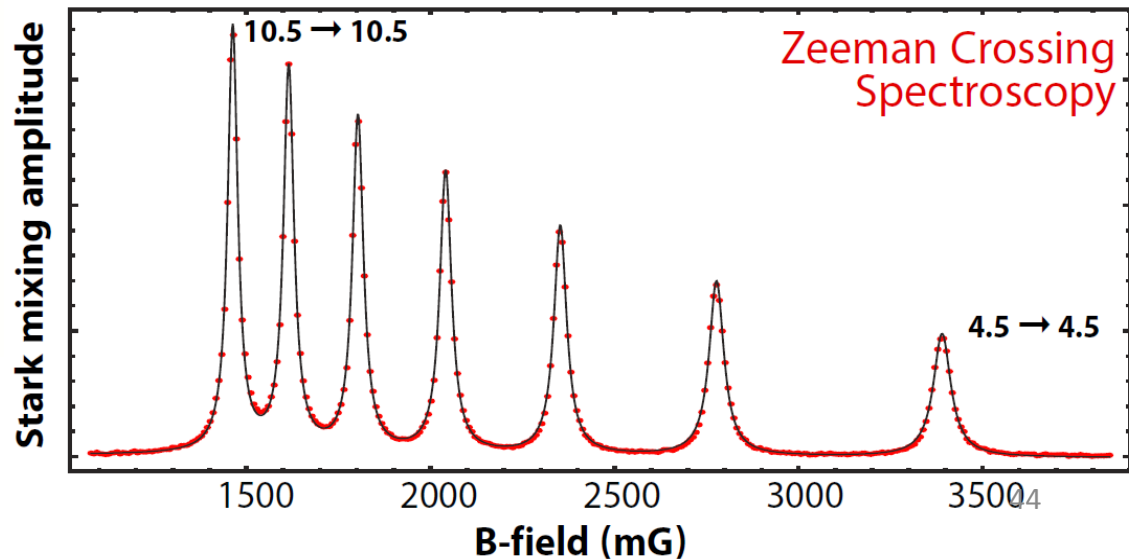
B: $4f^9 5d^2 6s$
 $F = 10.5, \tau > 200 \mu\text{s}$
 $g_F = 1.257$



A: $4f^{10} 5d 6s$
 $F = 10.5, \tau \sim 8 \mu\text{s}$
 $g_F = 1.112$

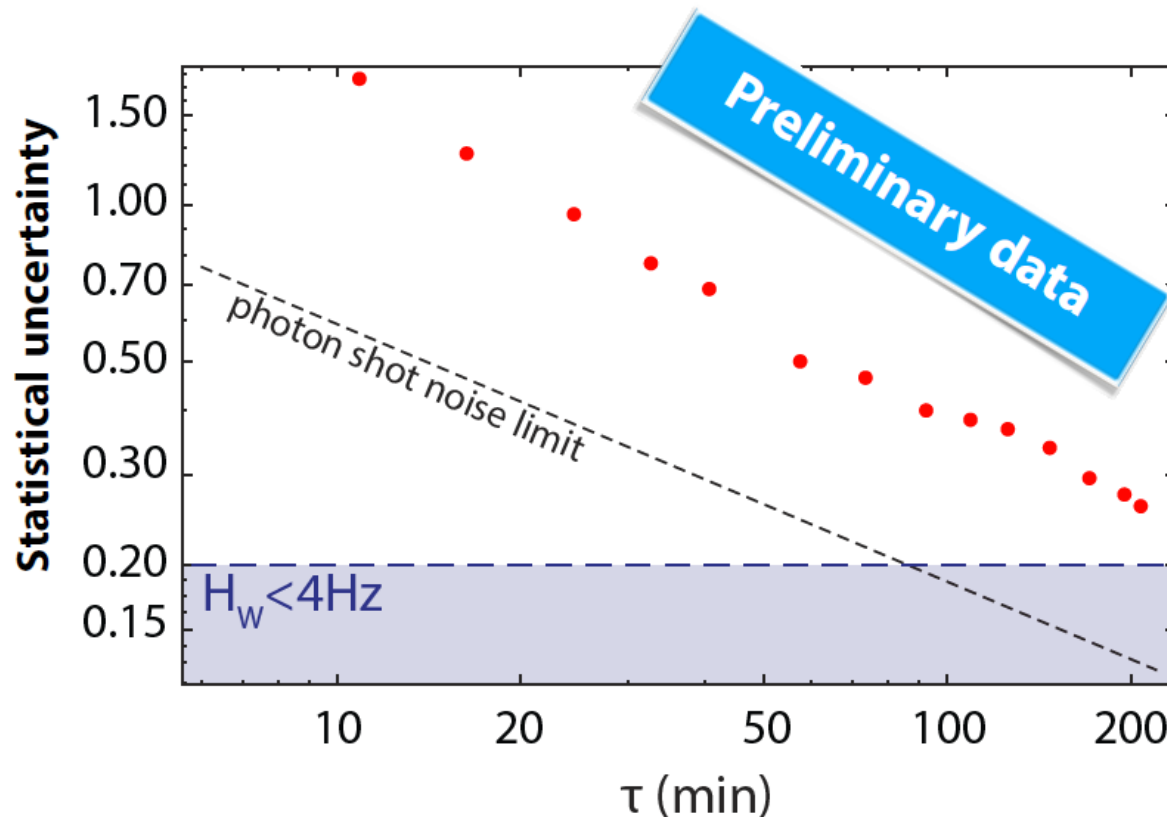
Allowed Stark-PNC interference

$$\dot{\mathbf{E}} \cdot (\mathbf{B} - \mathbf{B}_{\text{crossing}})$$



Dy setup upgrades & current status

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





Dr. L. Bougas



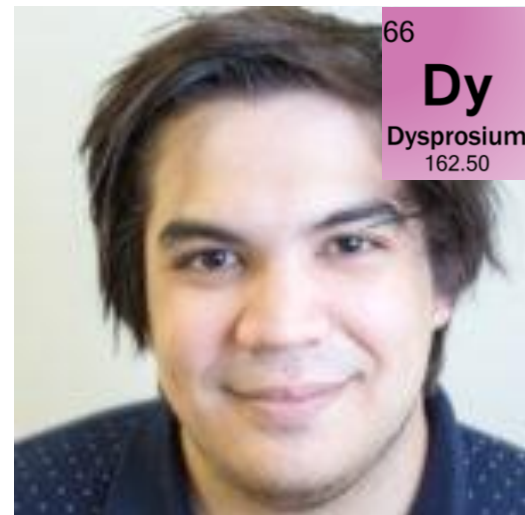
Dr. A. Sharma



A. Frabricant



Prof. D. Budker



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**)

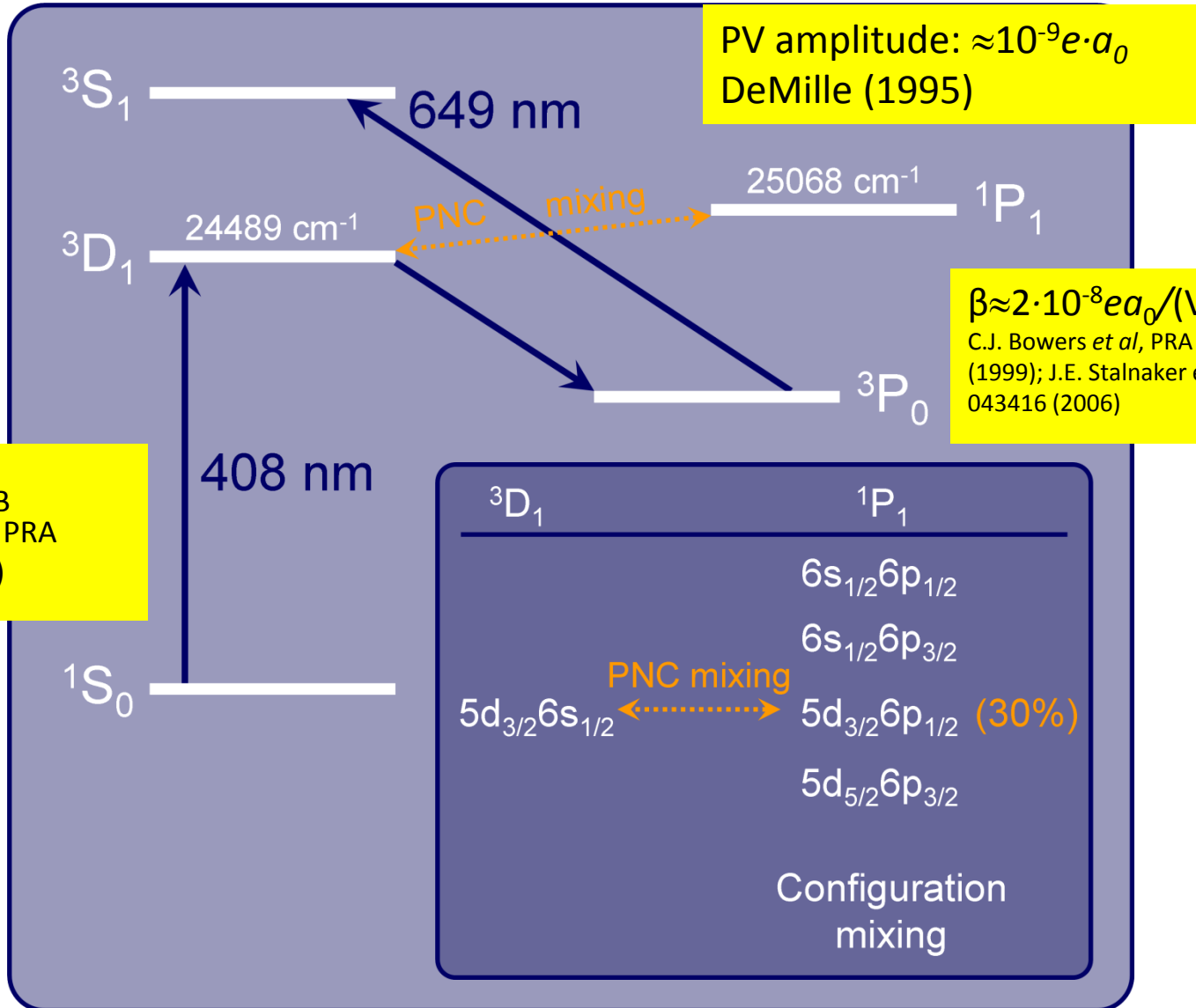
- ...1995 Boulder, Oxford, Seattle, Paris

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

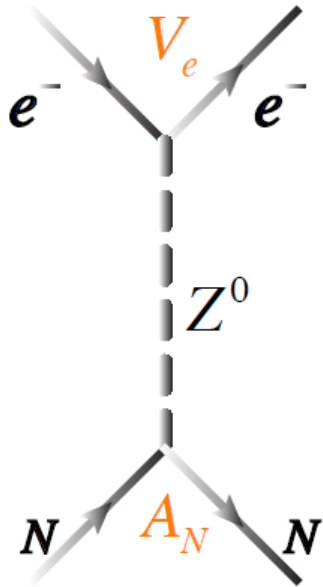


PV amplitude: $\approx 10^{-9} e \cdot a_0$
DeMille (1995)

$\beta \approx 2 \cdot 10^{-8} e a_0 / (\text{V/cm})$
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: $V_e \cdot A_N$



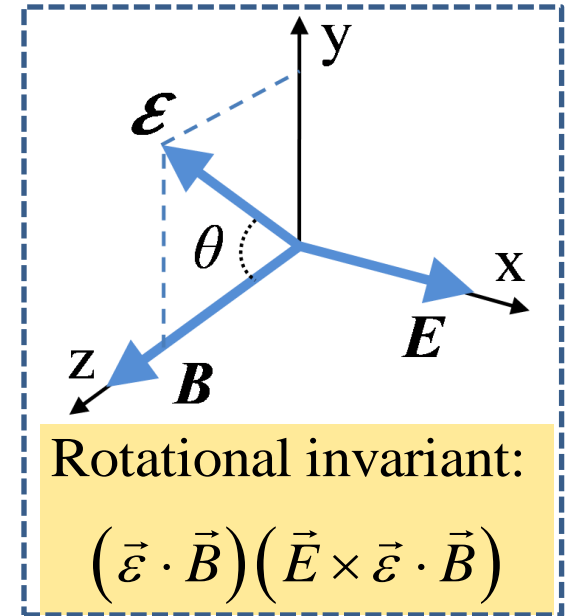
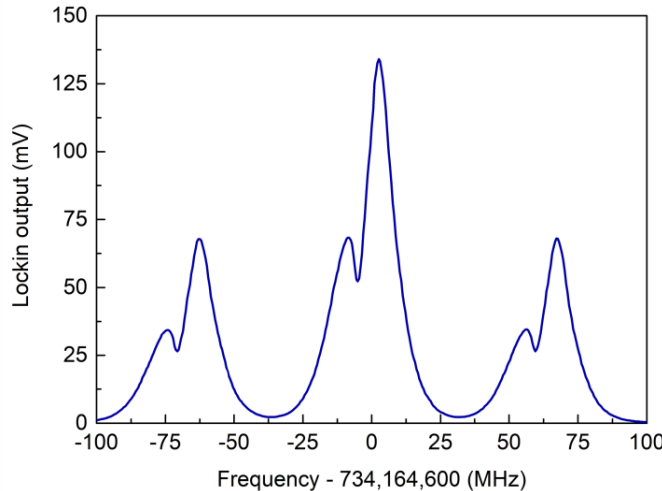
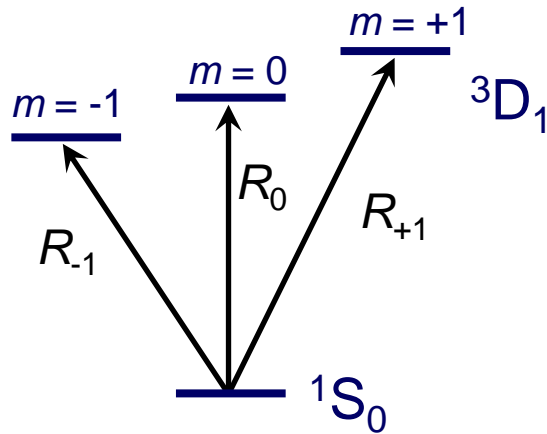
Only valence nucleon contributes

Suppressed by $\sim 10^3$ compared to NSI effect

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

$$\eta_{axial} = -C_N^{(2)} \frac{\kappa_N - 1/2}{I(I+1)} \quad N=p \text{ or } n$$

The Yb PV experiment



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

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 ($\pi/4 \Leftrightarrow -\pi/4$) 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

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

- 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.
 - Acquisition without power-build-up cavity .
 - Varying position on lineshape.
 - With left or right half of atom beam blocked.
- Measure “zero”: asymmetry on $^{171}\text{Yb } F=1/2 \rightarrow F'=1/2$ transition.
- Measure PV on $m=\pm 1$ 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.