Atomic parity violation in Yb and Dy

D. Antypas

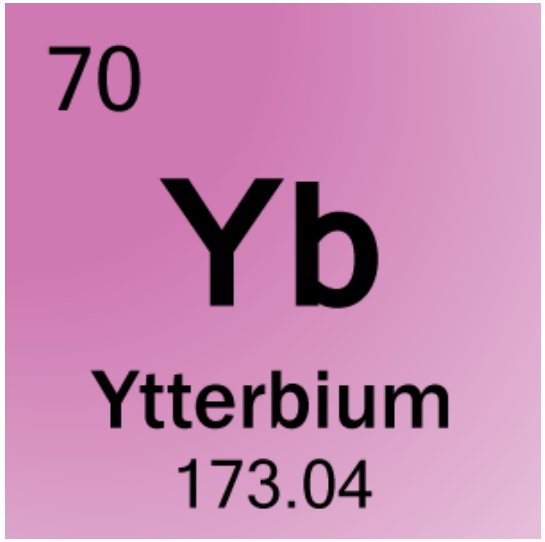
SSP 2018

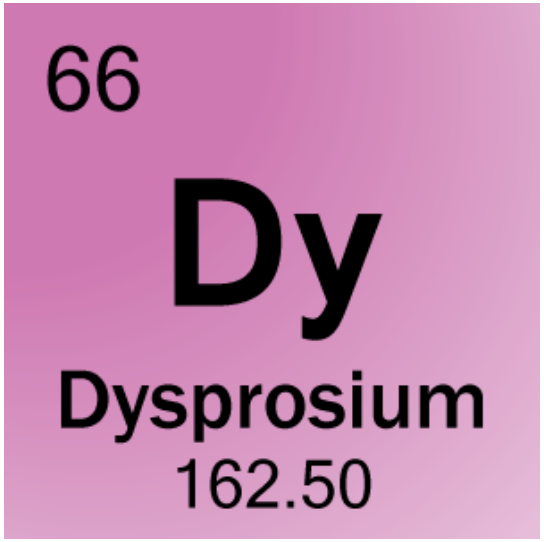
GSI

HIM
Helmholtz-Institut Mainz

JG|U

Atomic Parity Violation at the Helmholtz-Institut Mainz





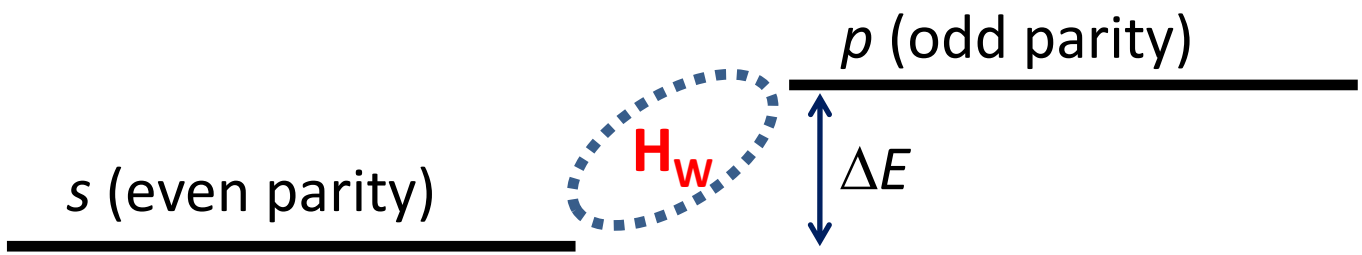
Dionysis Antypas
Anne Fabricant

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)



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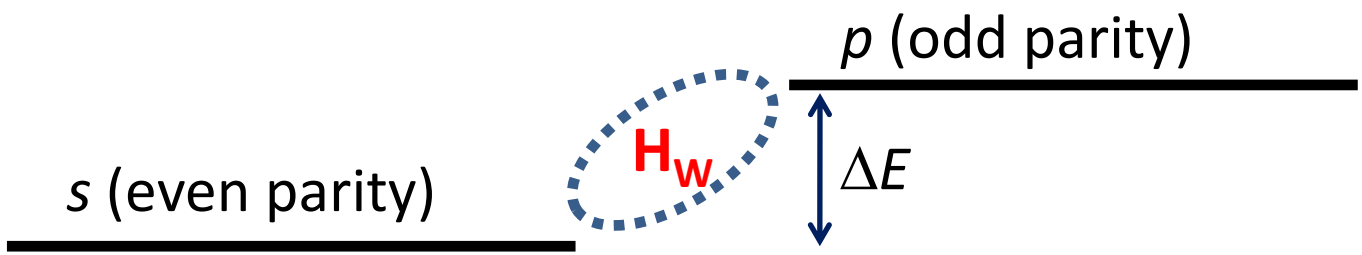


$$s \to s + i\varepsilon p;\ p \to p + i\varepsilon s$$

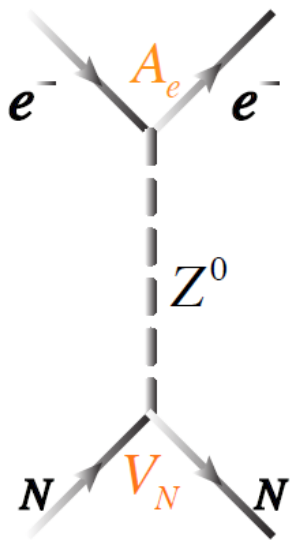
$$\varepsilon = \frac{\langle s | H_W | p \rangle}{\Delta E} \sim \frac{Z^3}{\Delta E}$$ - the Bouchiat Law

Atomic Parity Violation Enhancement:

- Heavy atoms (high Z)
- Small ΔE

Atomic Parity Violation: Main processes

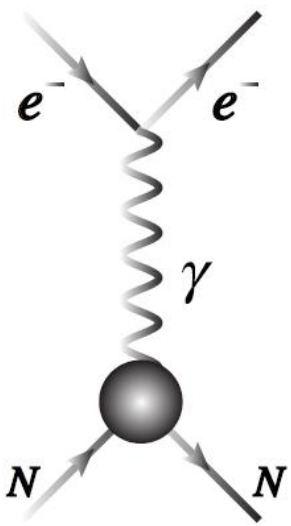
Nuclear-Spin Independent process



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

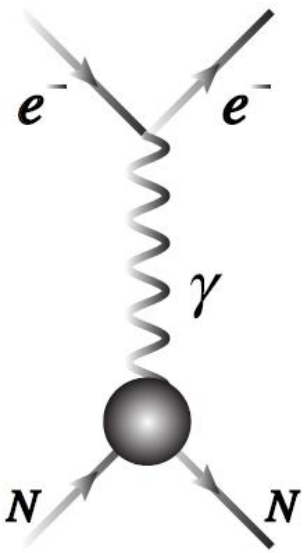
- Probe of the Standard model parameter θ_W
- Test of SM and constraints on physics beyond SM, including various "dark sector" scenarios

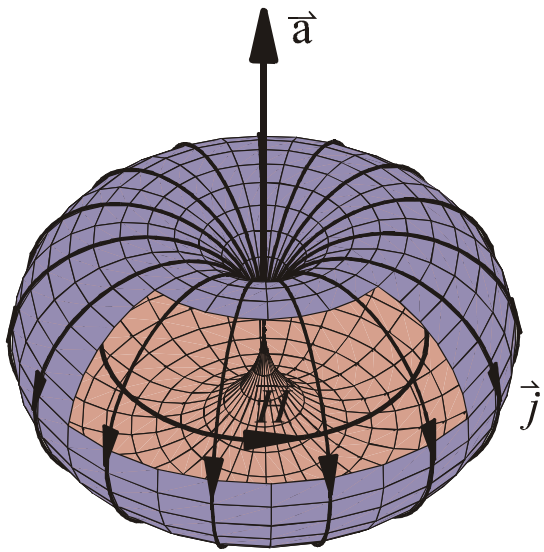
Main Nuclear-Spin Dependent process

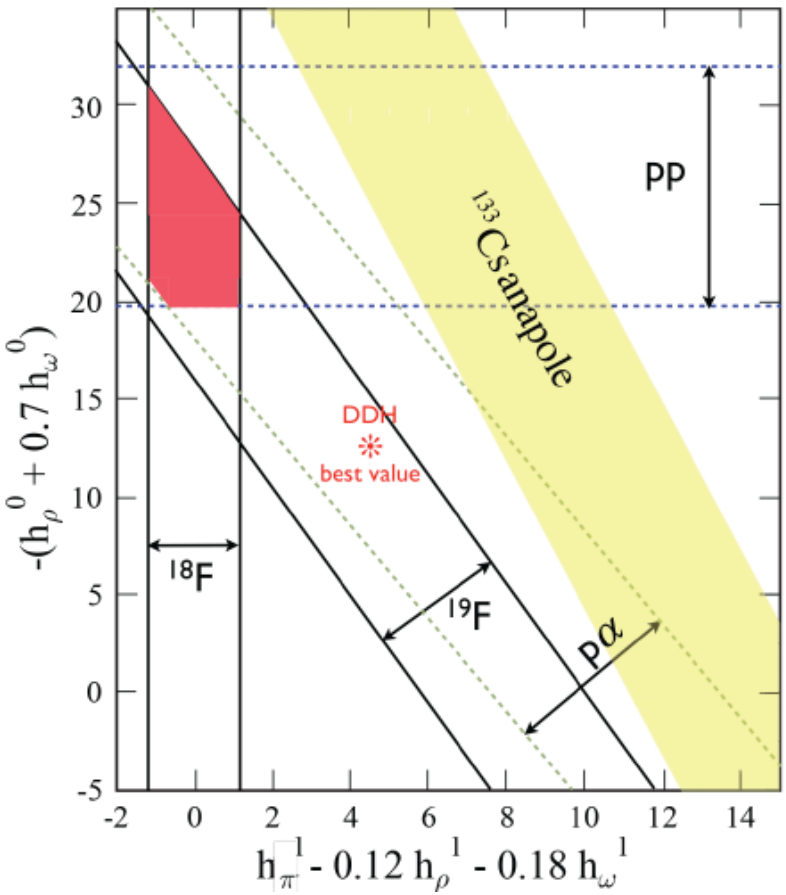


Anapole moment-hadronic PV

Motivation I: anapole moment







Safranova et al. arXiv:1710.01833

Anapole moment:

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

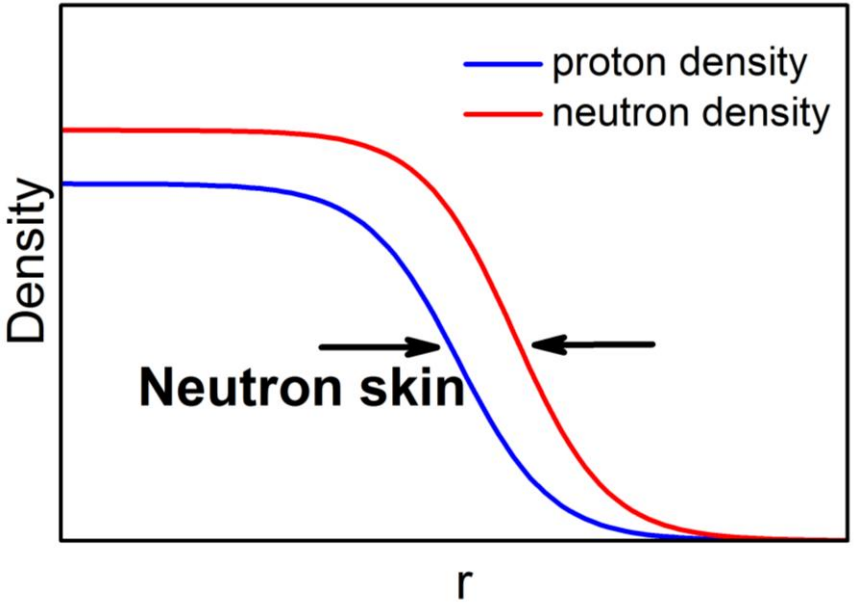
Motivation II: neutron skins

Weak charge: $Q_W = -N + Z\cdot(1 - 4\sin^2\theta_W)$

What is probed however is:

$$Q'_W = -N\cdot\boldsymbol{q_n} + Z\cdot\boldsymbol{q_p}\,(1 - 4\sin^2\theta_W)$$

$$q_{n(p)} = \int f(r)\rho_{n(p)}(r)\,dr$$



Neutron skin contribution between ^{170}Yb - ^{176}Yb isotopes:

$\Delta Q_W / Q_W \sim 0.1\%$

Why PV with ytterbium

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

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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

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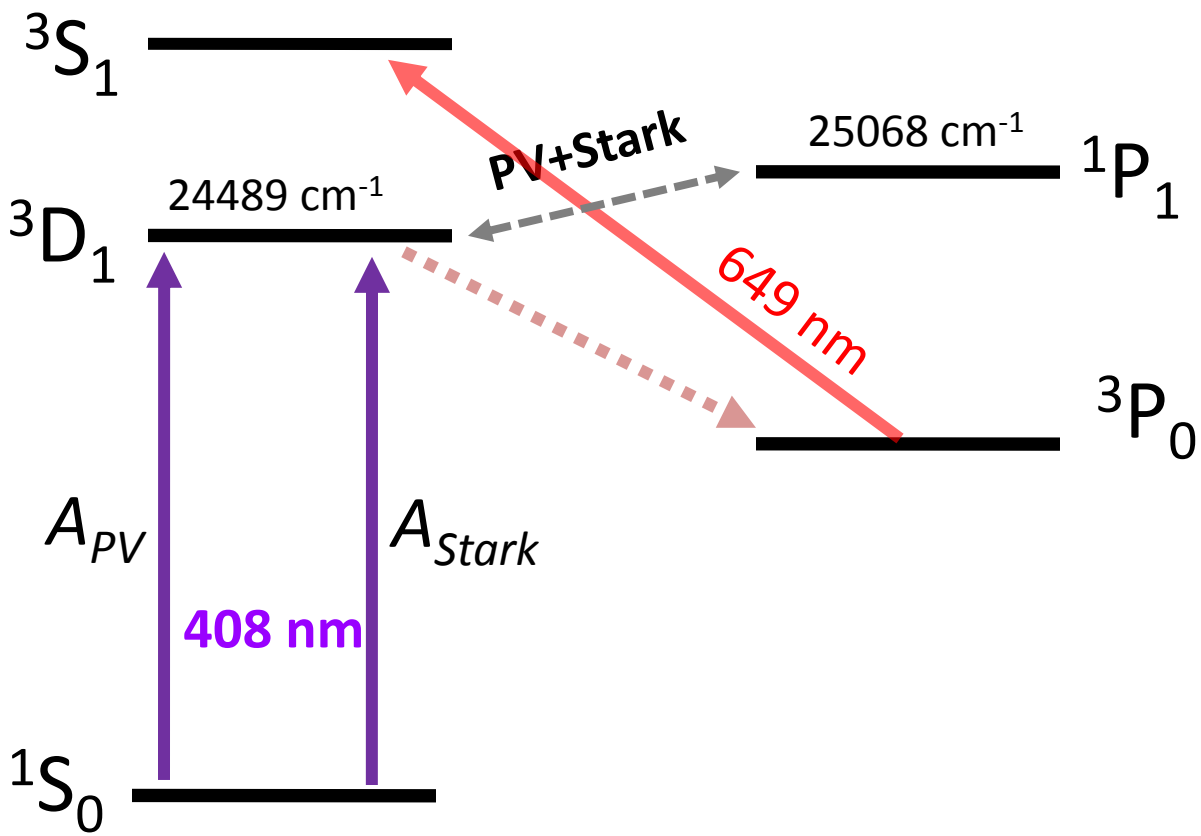
- PNC on chain of isotopes → neutron distributions
- Two isotopes with nuclear spin → anapole moment

The Yb PV experiment



Stark-PV interference

$$R \propto \left| A_{Stark} + A_{PV} \right|^2 \approx \beta^2 E^2 \sin^2\theta + \boxed{2E1_{PV}\,\beta E \cos\theta \sin\theta}$$

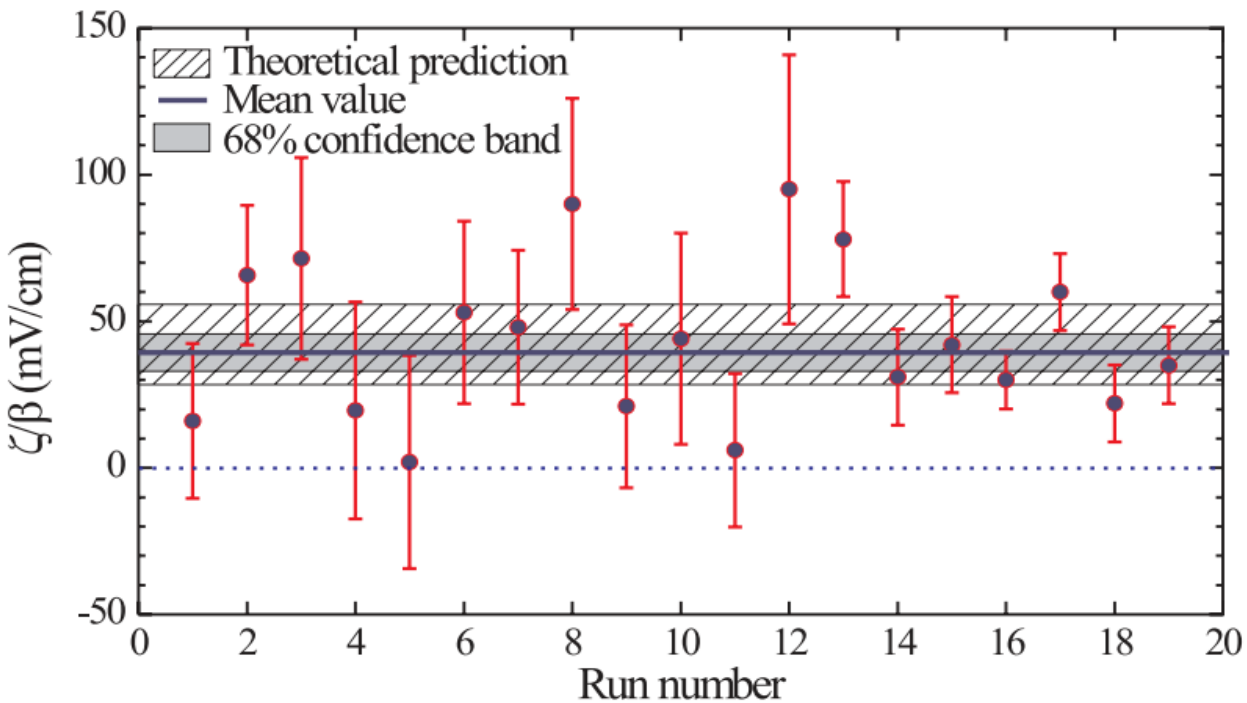
Reverse E (20 Hz) & θ (0.2 Hz) and measure $E1_{PV}/\beta$

^{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]

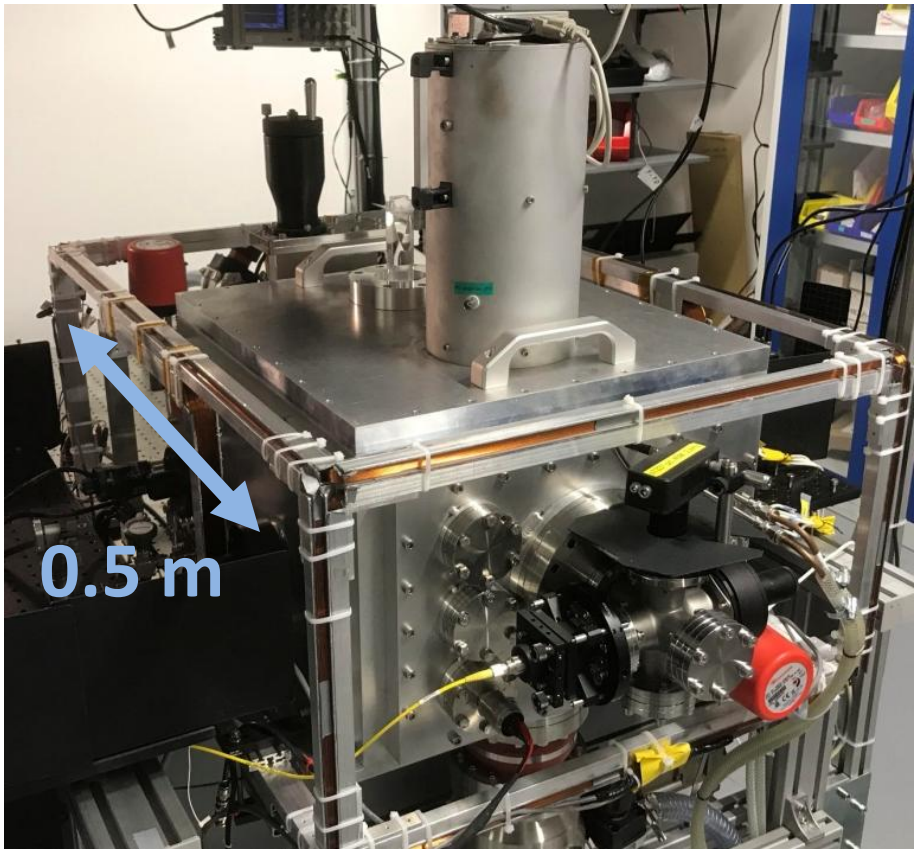


Mean value: $39(4)_{\text{stat}}(5)_{\text{syst}}$ mV/cm, $|\zeta| = 8.7 \pm 1.4 \times 10^{-10} ea_0$

Yb reincarnation in Mainz

New apparatus

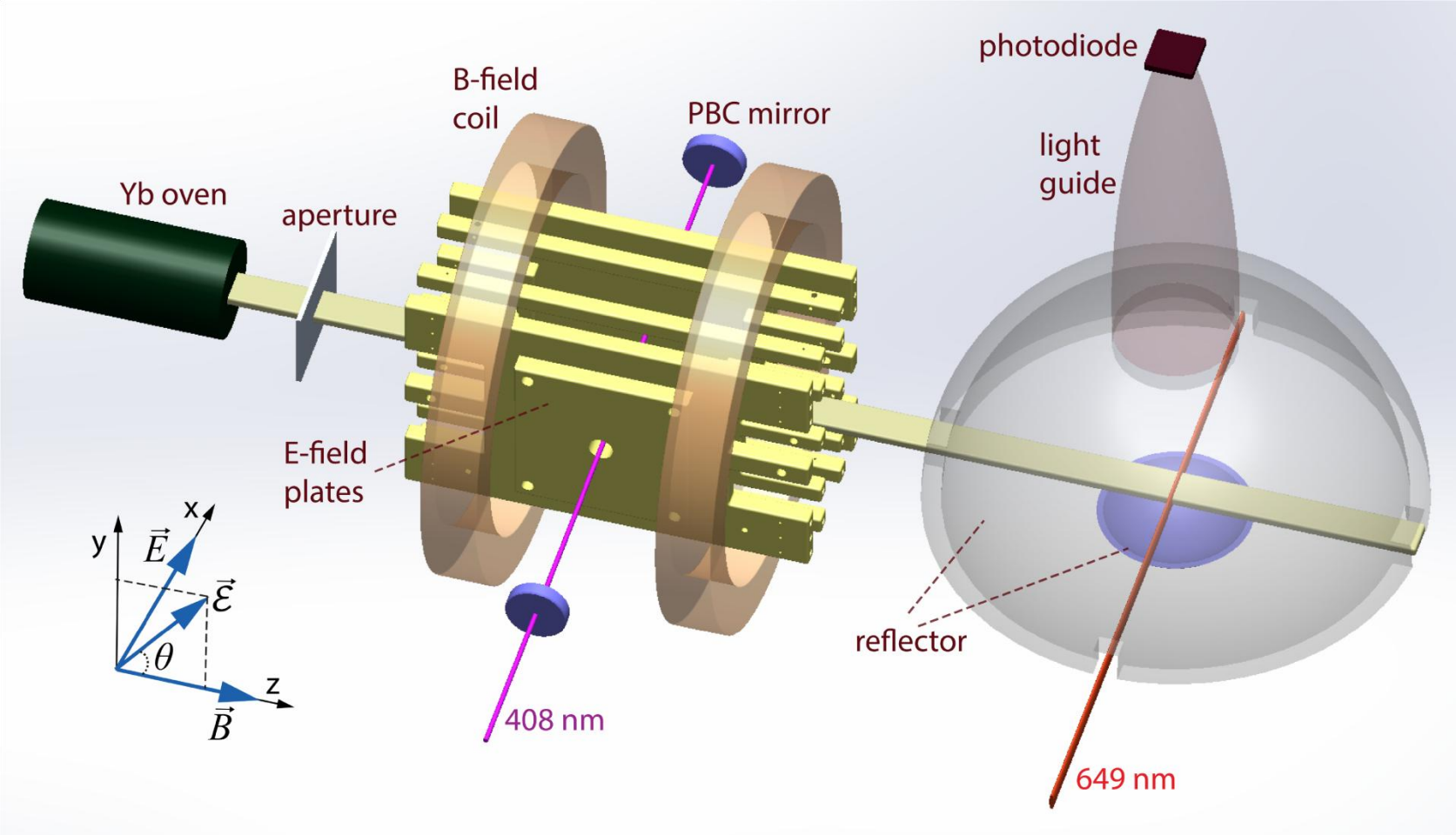
- Newly built vacuum system
- More powerful and frequency stable laser system
- More precise control of fields applied in interaction region
- 20 times better SNR



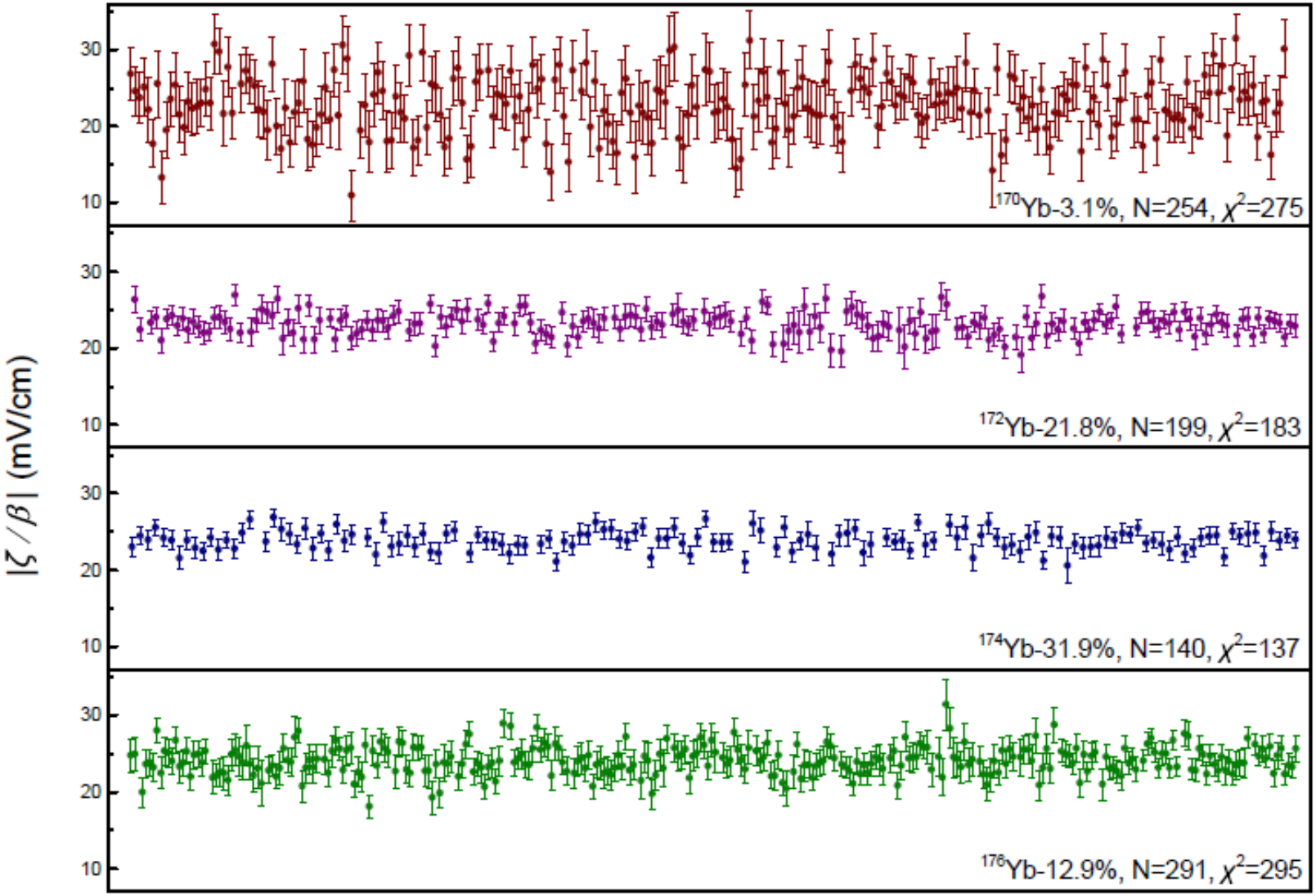
Mainz Roadmap

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

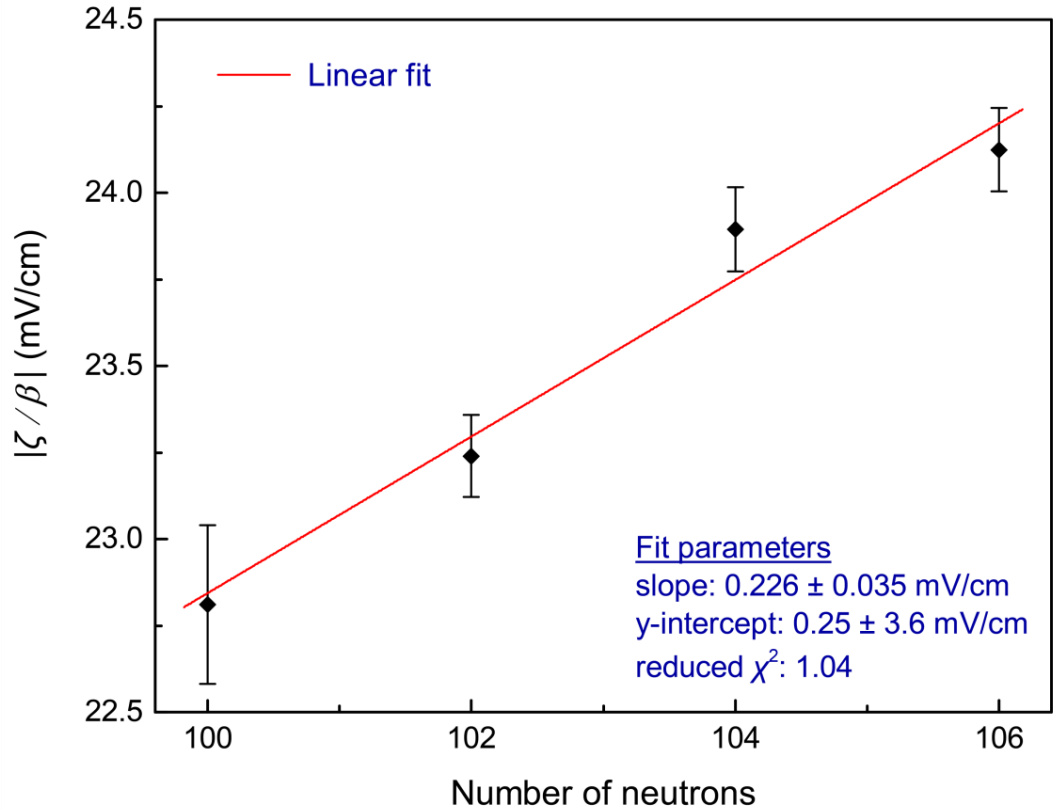
Apparatus schematic



Early 2018 run in 4 spin-zero isotopes



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

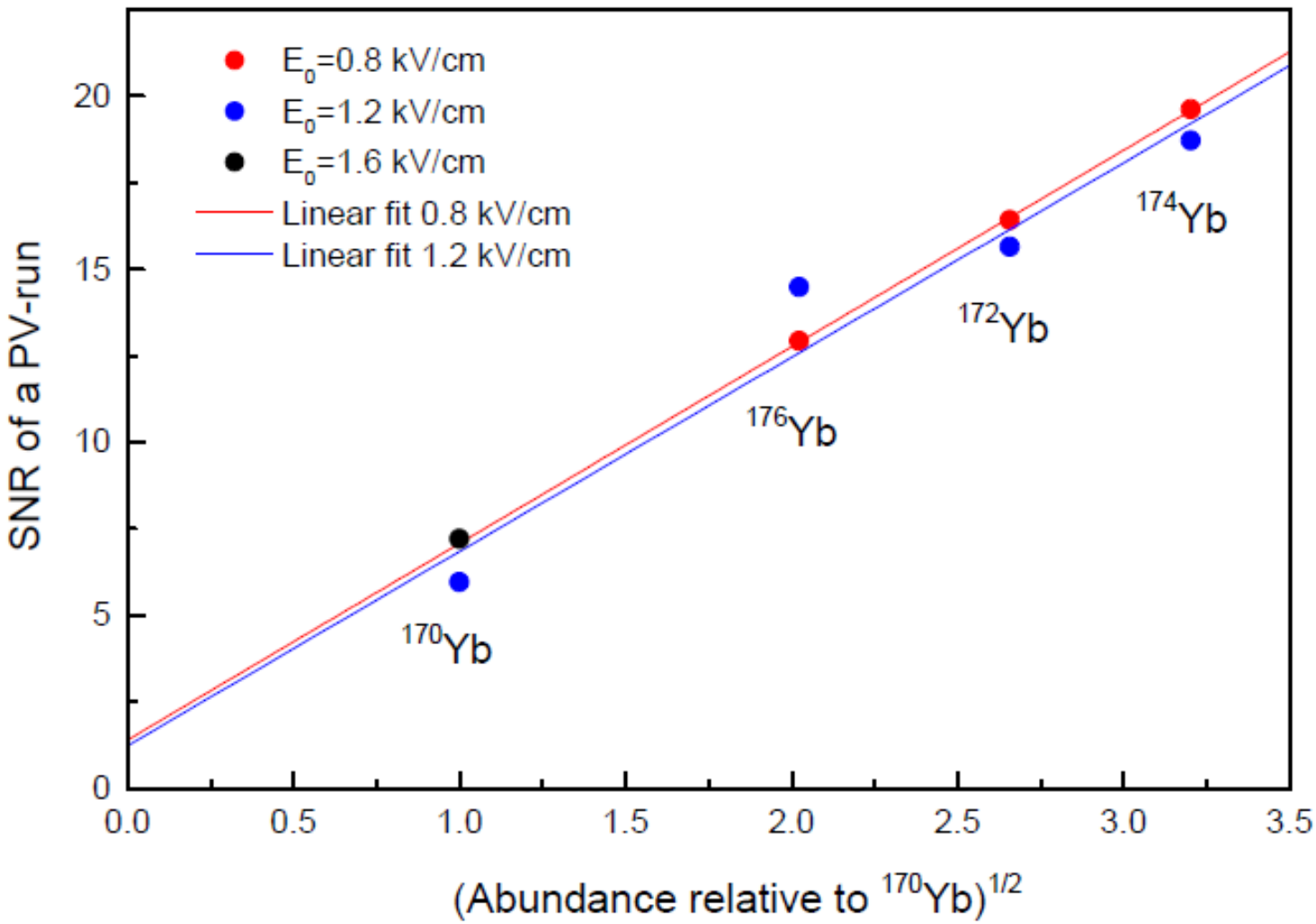
Single isotope measurement uncertainties

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 → Stray fields & field-misalignments

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

Yb PV measurement sensitivity



Next stop: anapole moment

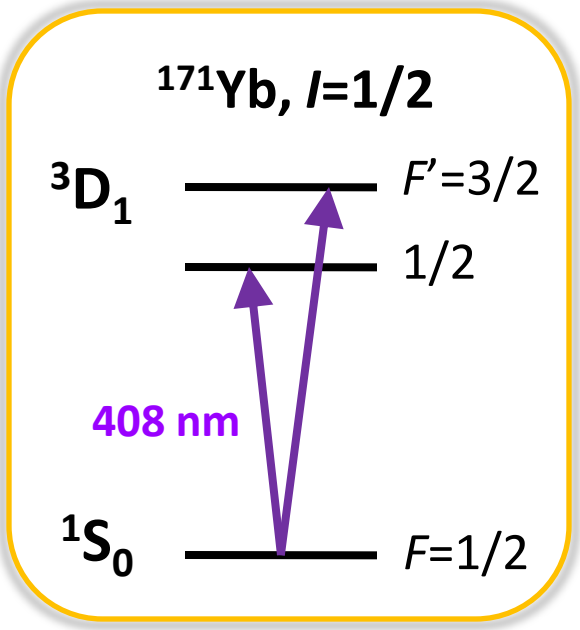


Table 1
Nuclear spin-dependent P-odd amplitudes $E1_{SD}$ are in units of $(\kappa e a_0 \times 10^{-11})$, A is the number of nucleons in the nucleus.

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 ^{171}Yb F'=3/2 and F'=1/2 ~ 0.1%

Need to boost SNR!

Yb sensitivity improvements (in progress)

Need x10 sensitivity enhancement for anapole, neutron skins

- Boost the Yb oven flux (x7 signal increase)
- Increase interaction region width (x2)
- Power build-up cavity mirrors upgrade (x2)
- Integrate longer…

Atomic PV in Dy

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

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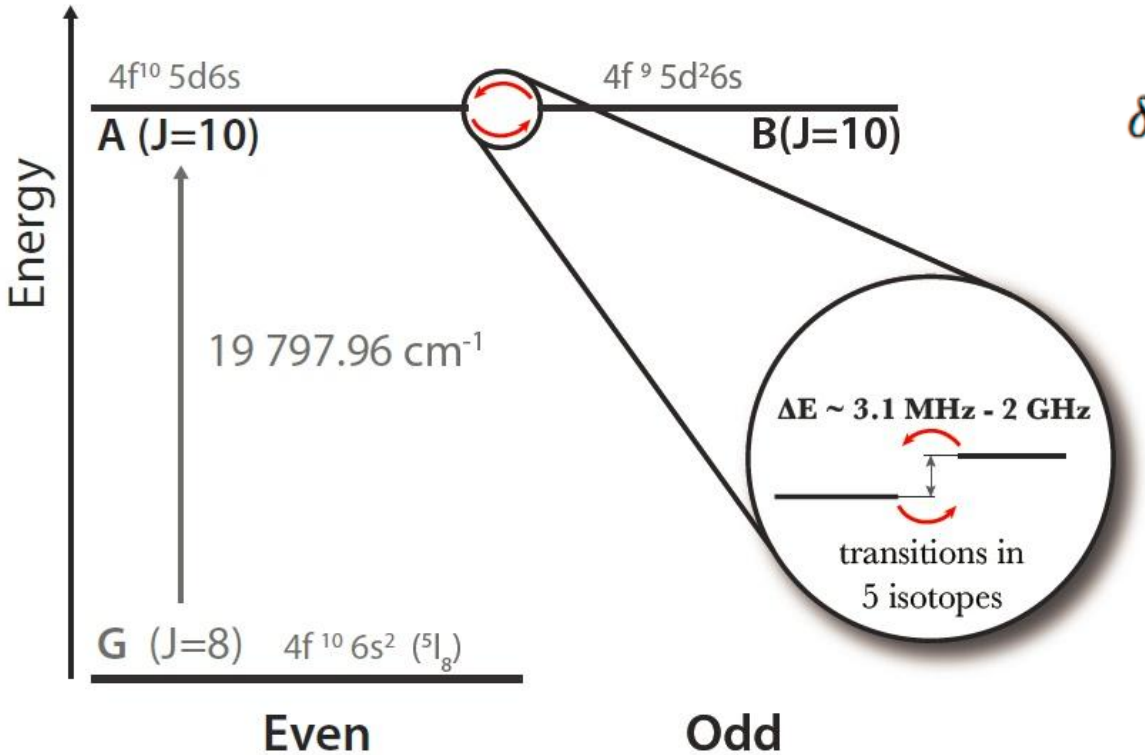

$$\delta_W = \frac{\langle n'p|H_W|ns\rangle}{\Delta E} \sim Z^3$$

Theory (1994)

$|H_W|=70 \pm 40$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…

PHYSICAL REVIEW A VOLUME 56, NUMBER 5 NOVEMBER 1997

Search for parity nonconservation in atomic dysprosium

A. T. Nguyen,[1] D. Budker,[1,2] D. DeMille,[1,*] and M. Zolotorev[3]
[1]*Physics Department, University of California, Berkeley, California 94720-7300*
[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

A. T. Nguyen*
Department of Physics, University of California at Berkeley, Berkeley, California 94720-7300, USA

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and Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

S. K. Lamoreaux‡ and J. R. Torgerson§
University of California, Los Alamos National Laboratory, Physics Division, P-23, MS-H803, Los Alamos, New Mexico 87545, USA
(Received 28 August 2003; published 12 February 2004)

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

PRL **98,** 040801 (2007) PHYSICAL REVIEW LETTERS week ending 26 JANUARY 2007

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

A. Cingöz,[1] A. Lapierre,[1] A.-T. Nguyen,[2] N. Leefer,[1] D. Budker,[1,3] S. K. Lamoreaux,[2,*] and J. R. Torgerson[2]

[1]*Department of Physics, University of California at Berkeley, Berkeley, California 94720-7300, USA*

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(Received 1 September 2006; published 26 January 2007)

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

PRL **98,** 040801 (2007) PHYSICAL REVIEW LETTERS week ending 26 JANUARY 2007

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. Torgerson[3]

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

PRL **98,** 040801 (2007) PHYSICAL REVIEW LETTERS week ending 26 JANUARY 2007

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

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

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,‡]

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

PRL **98,** 040801 (2007) PHYSICAL REVIEW LETTERS week ending 26 JANUARY 2007

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

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

Transverse laser cooling of a thermal atomic beam of dysprosium

PRL **111,** 050401 (2013) PHYSICAL REVIEW LETTERS week ending 2 AUGUST 2013

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

M. A. Hohensee,* N. Leefer, and D. Budker

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C. Harabati, V. A. Dzuba, and V. V. Flambaum

School of Physics, University of New South Wales, Sydney 2052, Australia

(Received 14 March 2013; published 29 July 2013)

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

PRL **98,** 040801 (2007) PHYSICAL REVIEW LETTERS week ending 26 JANUARY 2007

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

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

Transverse laser cooling of a thermal atomic beam of dysprosium

PRL **111,** 050401 (2013) PHYSICAL REVIEW LETTERS week ending 2 AUGUST 2013

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

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

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

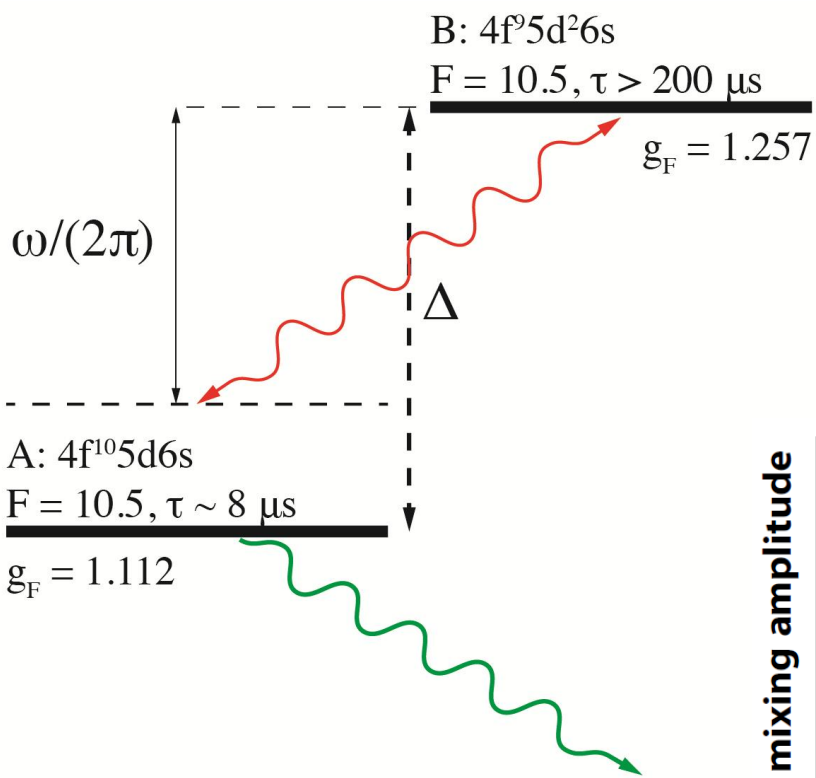
N. Leefer,[1] C. T. M. Weber,[2] A. Cingöz,[3] J. R. Torgerson,[4] and D. Budker[1,5]

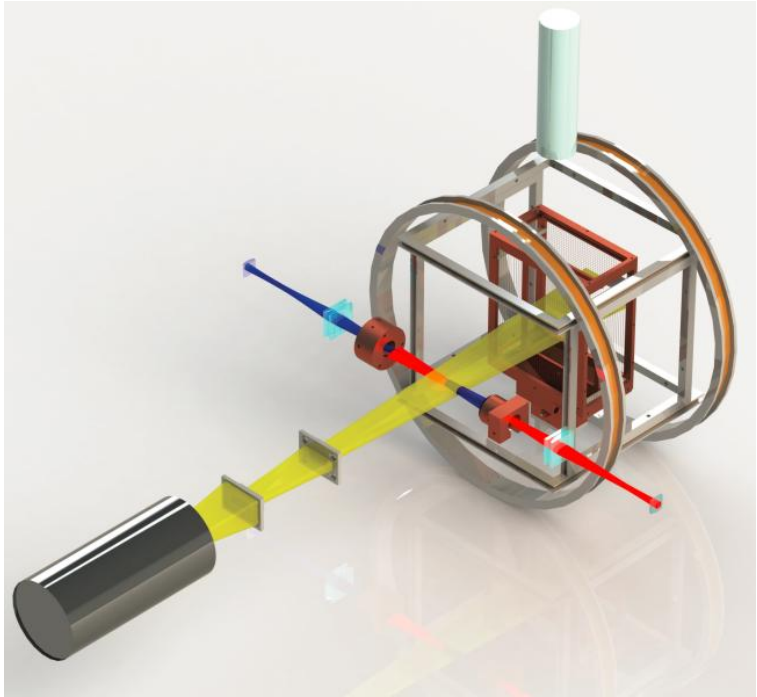
Revived Dy Atomic PV experiment

Improved theory (2010)

$|H_W| = 4 \pm 4$ Hz

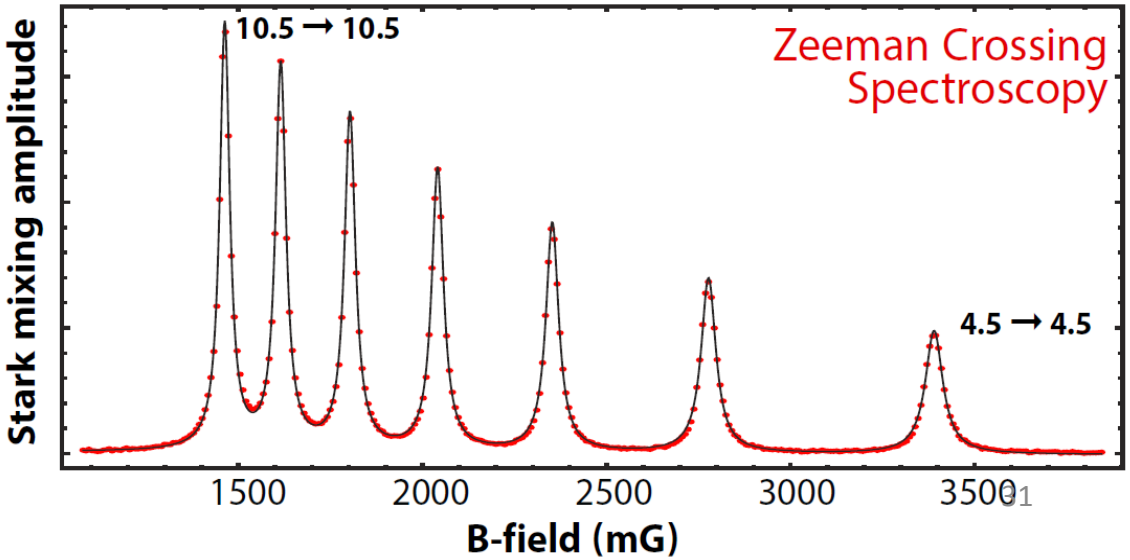
V. A. Dzuba & V. V. Flambaum,
PRA 81, 052515 (**2010**)





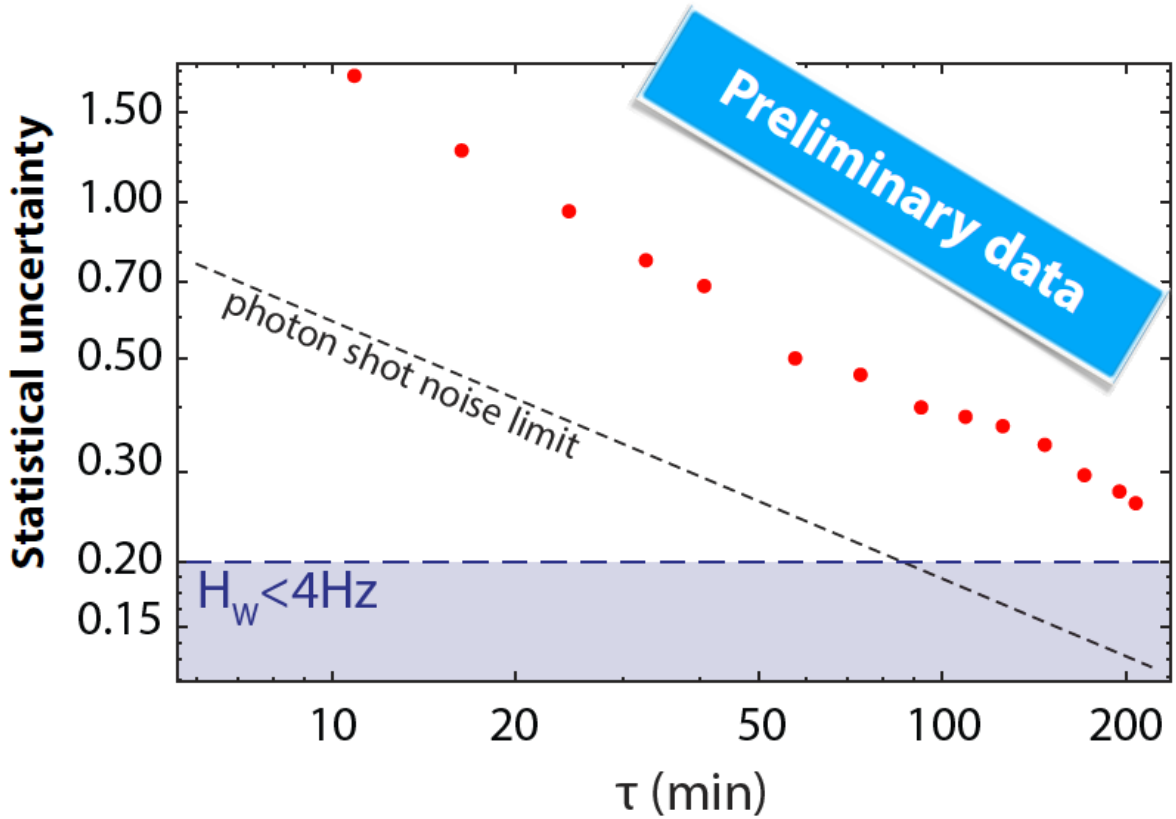
Allowed Stark-PV interference

$\dot{E} \cdot (B - B_{crossing})$

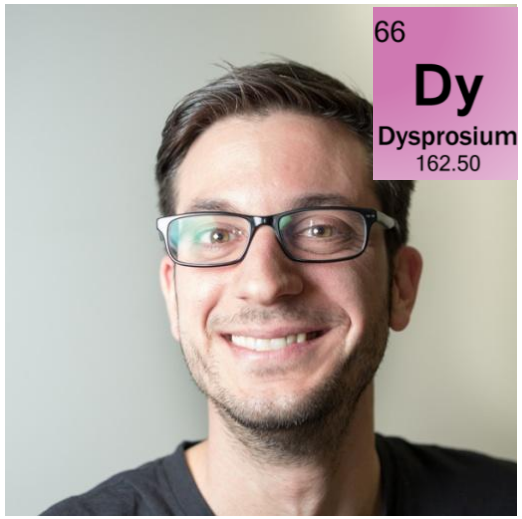


Dy setup upgrades & current status

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

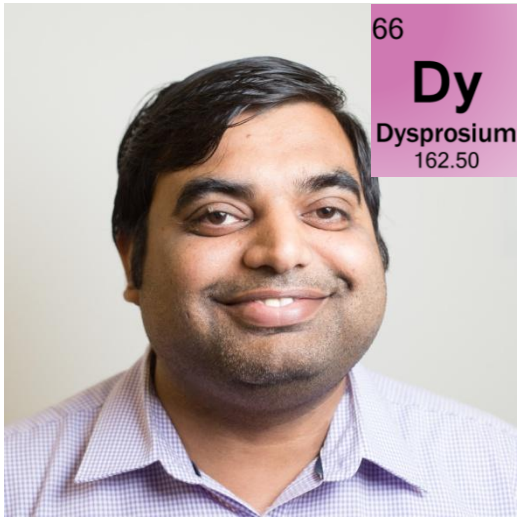


Mainz atomic PV crew



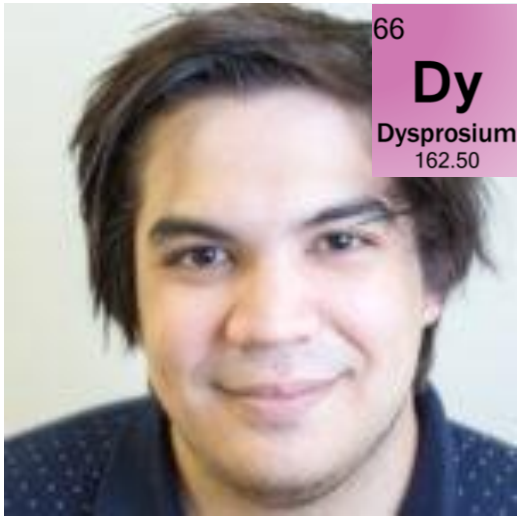
Dr. L. Bougas

Prof. D. Budker



Dr. A. Sharma

A. Frabricant



P. Leyser