Towards neutron skin and anapole moment measurements in atomic ytterbium

D. Antypas

MITP virtual workshop

"Parity Violation and Related Topics", 30.07.2020

JG|U

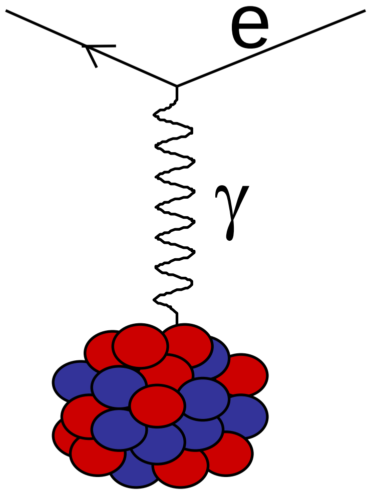
HIM
Helmholtz-Institut Mainz

Outline

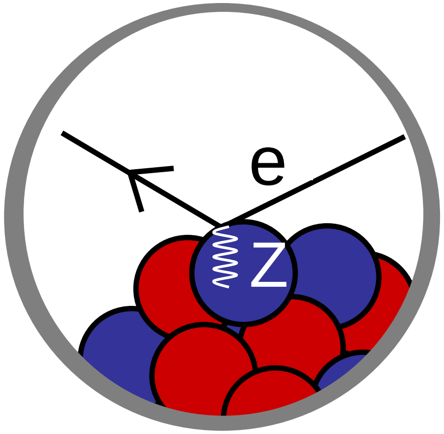
- Atomic parity violation background & motivations
- Yb parity violation experiment
- Isotopic variation of parity violation in Yb
- Current status, prospects for neutron skin and anapole measurements

Atomic Parity Violation

Main Source: Z exchange



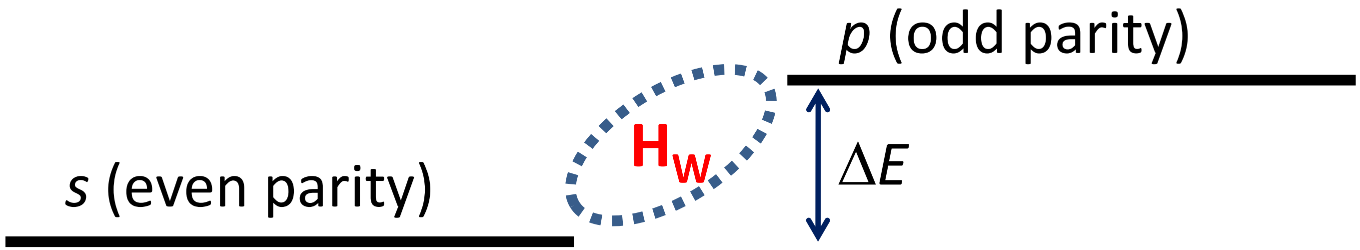
Electromagnetic interaction
(conserves parity)



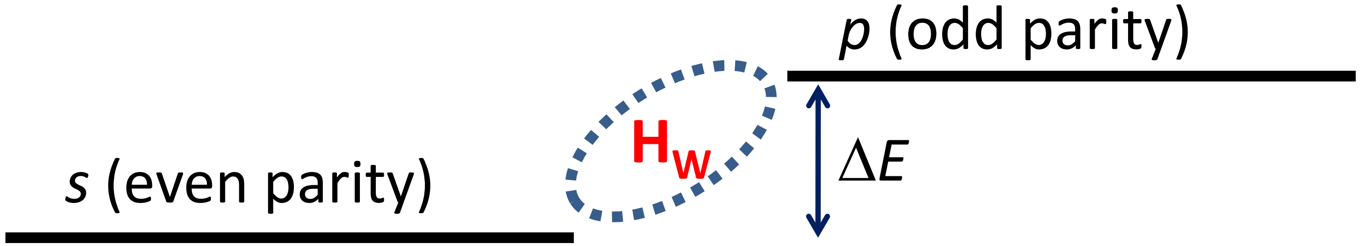
Weak interaction
(violates parity)

P-odd, T-even effect: $\vec{\sigma} \cdot \vec{p}$

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



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



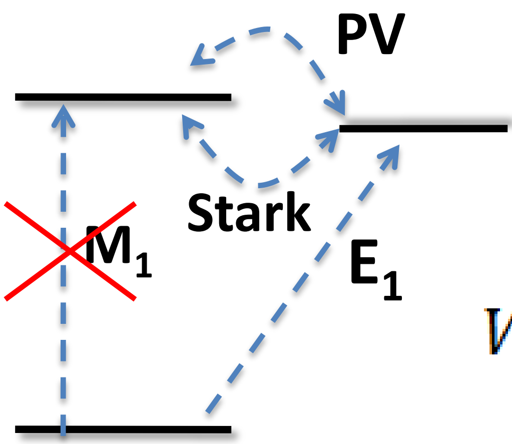
$$s \rightarrow s + i\varepsilon p;\ p \rightarrow p + i\varepsilon s$$

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

Atomic Parity Violation Enhancement:

- Heavy atoms (high Z)
- Small ΔE

How to measure parity violation on forbidden transitions?



☛ **Stark-interference technique**
Bouchiat & Bouchiat

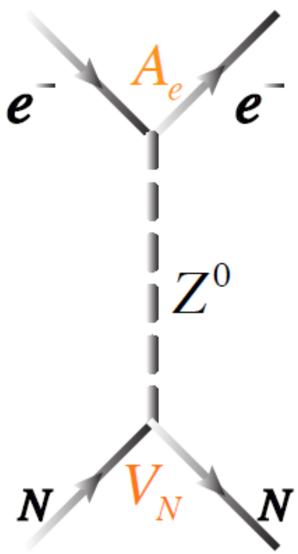
$$W_{\pm} = |A_{Stark} + A_{PV}|^2$$

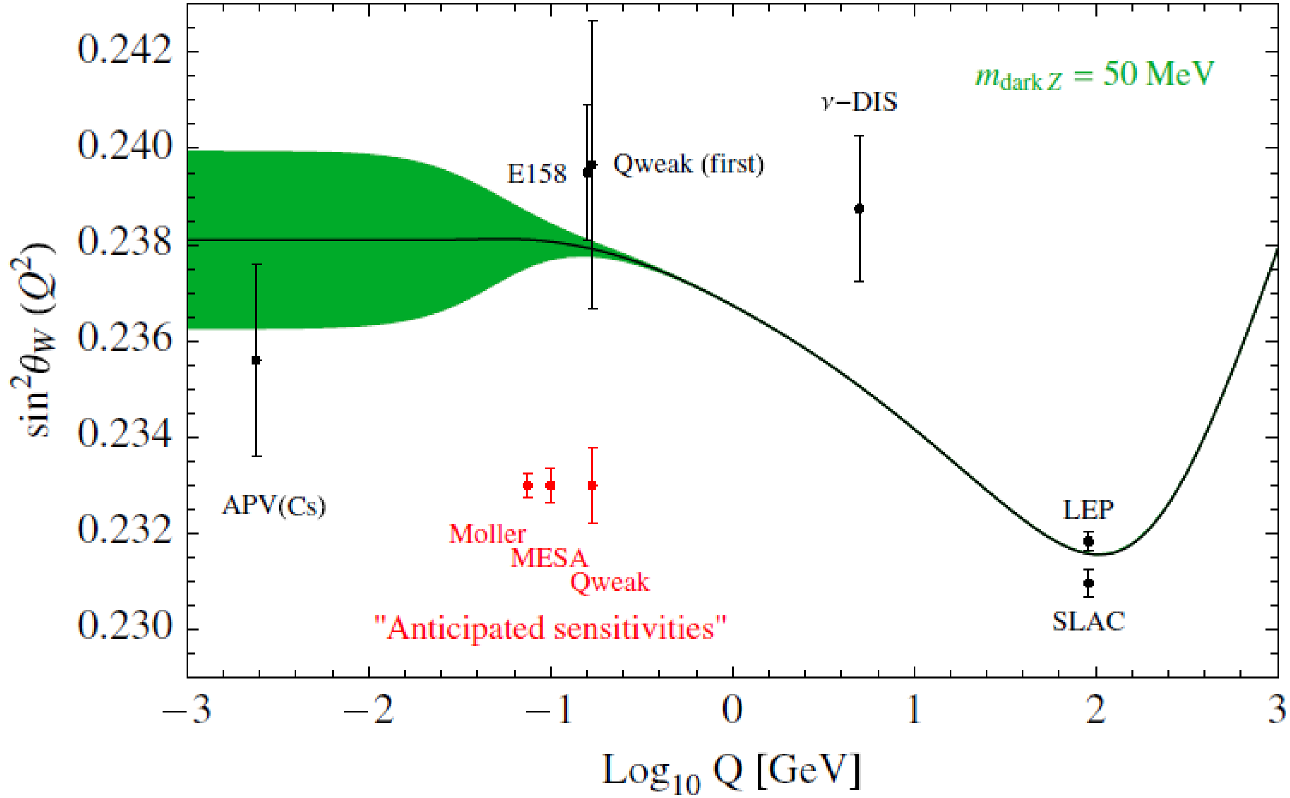
$$\approx \underbrace{A_{Stark}^2}_{P-conserving} \quad \underbrace{\pm 2A_{Stark} \cdot A_{PV}}_{P-violating}$$

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

- Several reversals available to extract PV signal

Nuclear spin-independent atomic PV





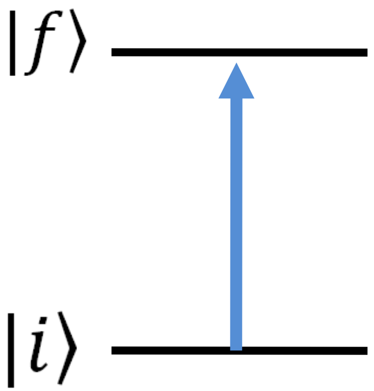
$$Q_W \approx -N + Z(1\text{-}4\sin^2\theta_W)$$

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

- Probe of the nuclear weak charge Q_W
- Constrain beyond Standard Model scenarios

Isotopic ratios & new physics

- 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 & new physics

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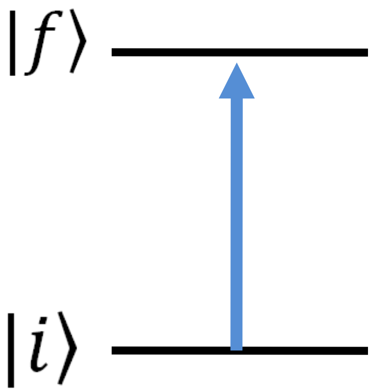

$$E1_{PV} = \langle f | D | i \rangle$$

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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 & neutron skins

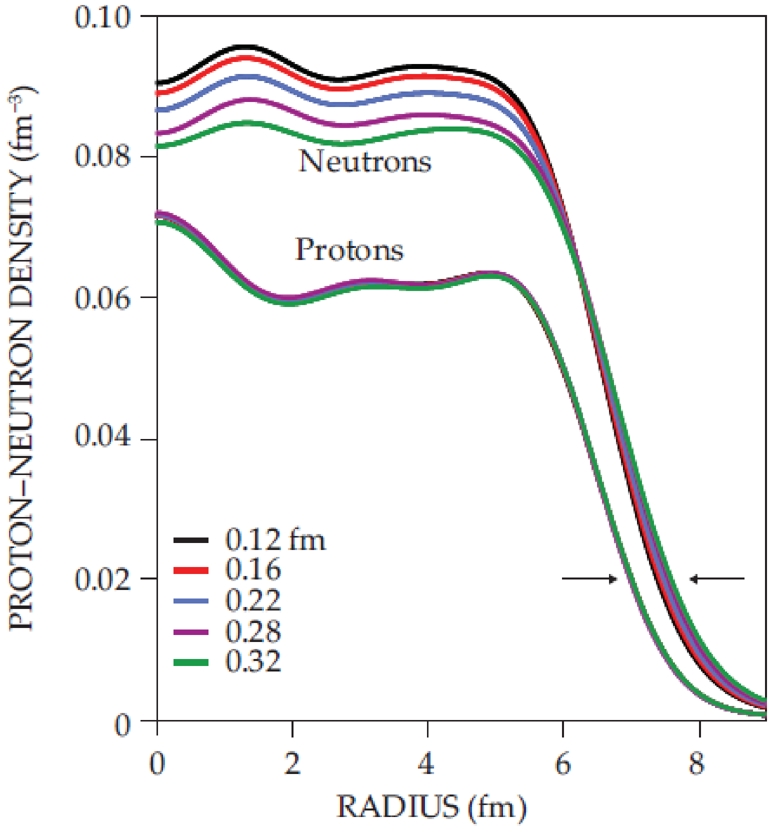
- How well does k_{PV} cancel in the ratio?

$$E1_{PV} = k_{PV} Q_W$$

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

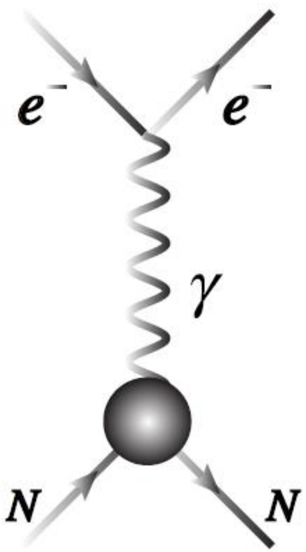
$$\frac{E1_{PV}}{E1'_{PV}} = 1 + \frac{\Delta N}{N} + \boxed{+\frac{3}{7}(aZ)^2 \frac{\Delta R'_{ns} - \Delta R_{ns}}{R_p}}$$

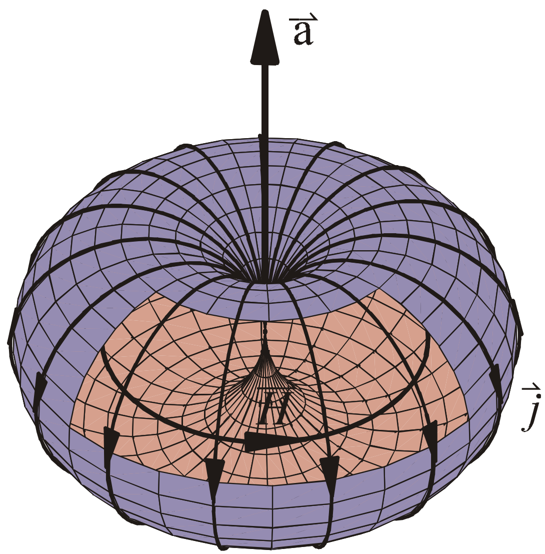
Skin contribution for ^{170}Yb - ^{176}Yb Isotopes ~ 10^{-3}

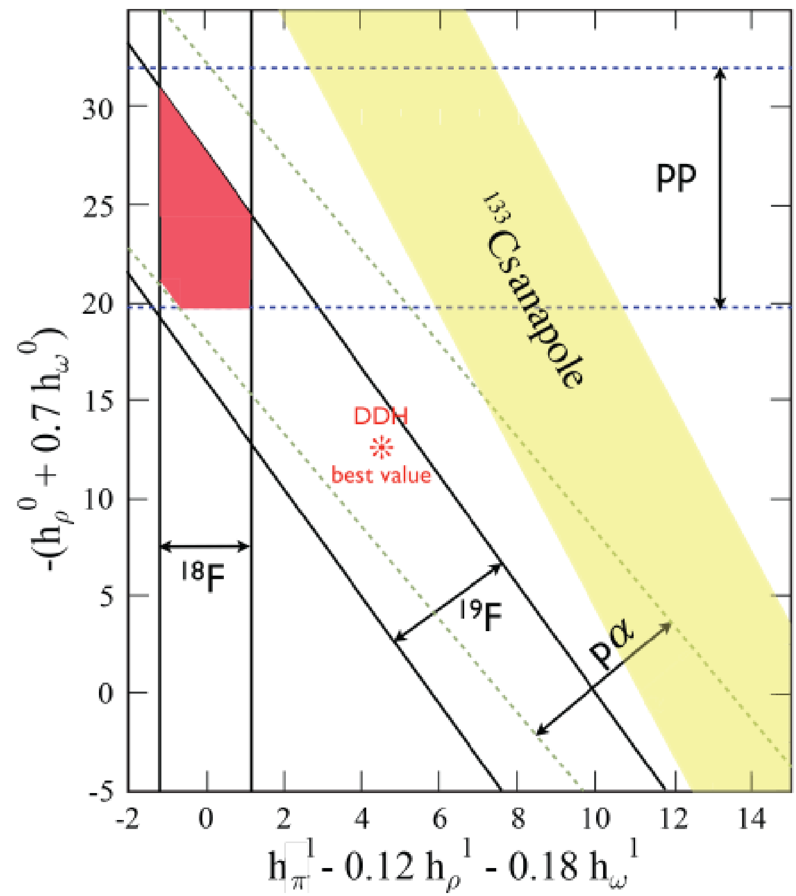


Piekarewicz and Fattoyev
Physics Today 72, 30 (2019)

Nuclear-spin-dependent PV: anapole moment





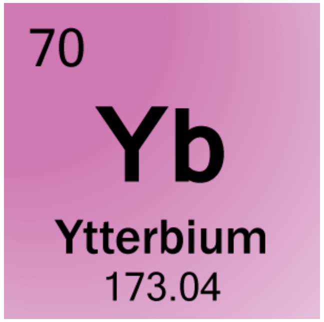


Safronova et al. arXiv:1710.01833

Anapole moment:

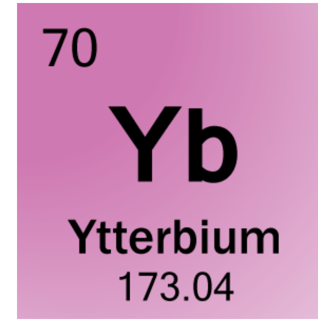
- P-odd E/M moment from intranuclear PV
- Probe of weak meson-nucleon couplings (hadronic PV)

Why PV with ytterbium



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

Why PV with ytterbium

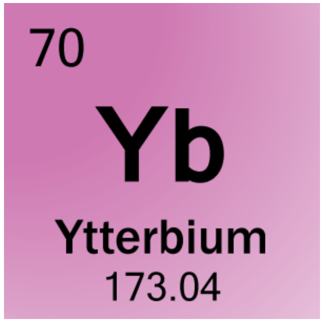


- **Large** PV effect (DeMille, 1995 - Tsigutkin *et al,* 2009)
- 7 stable isotopes (A=168, 170-174,176)

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

Why PV with ytterbium



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^{171}Yb	14.3	1/2
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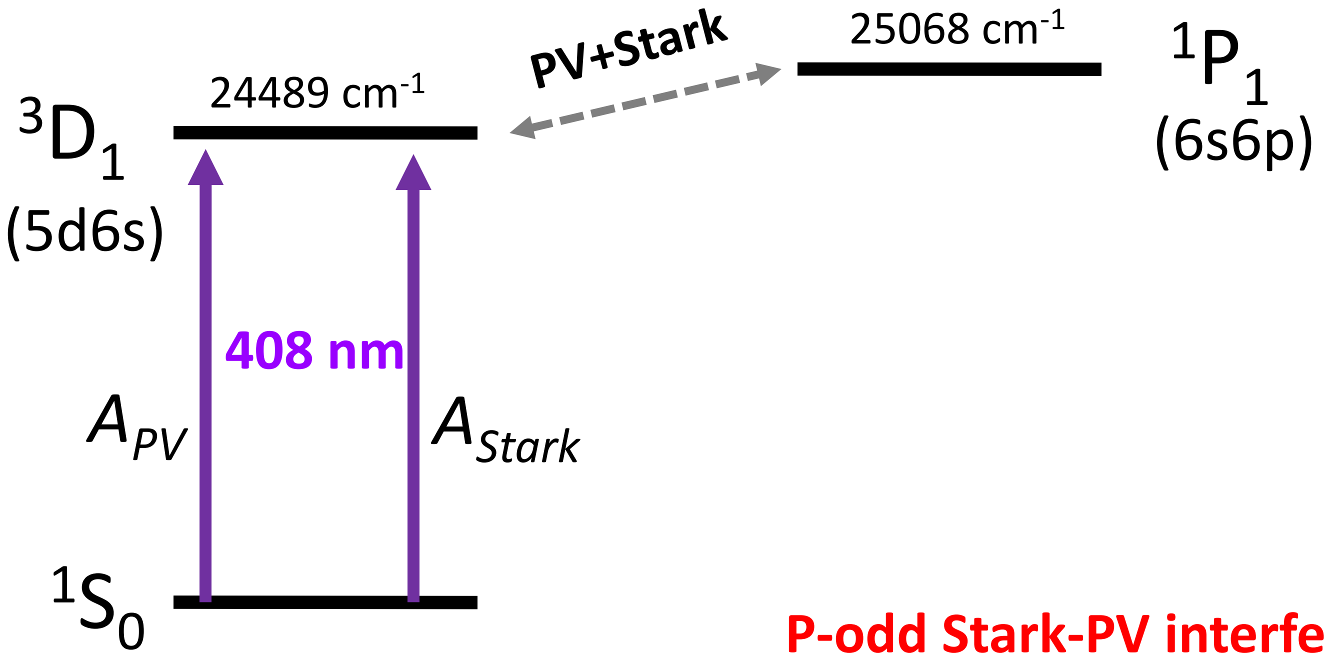
- PNC on chain of isotopes → neutron distributions
- Two isotopes with nuclear spin → spin-dependent PV effects

The Yb PV experiment



P-odd Stark-PV interference

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

- Reverse electric field: $E=E_0\cos(\omega t)$, measure harmonics ratio

$$r(\theta)=(4\zeta/\beta E_0)\cot\theta$$

- Extract ζ/β from the asymmetry: $r(\pi/4) - r(-\pi/4)$

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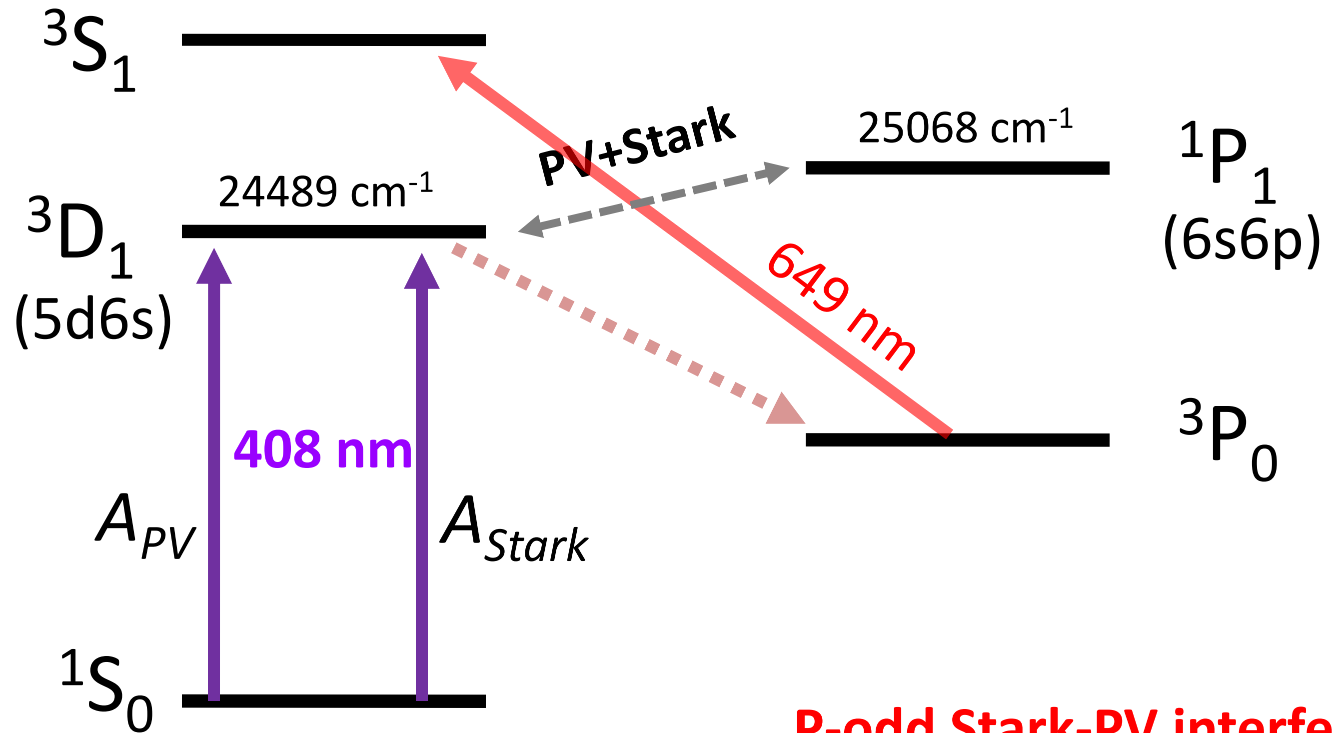

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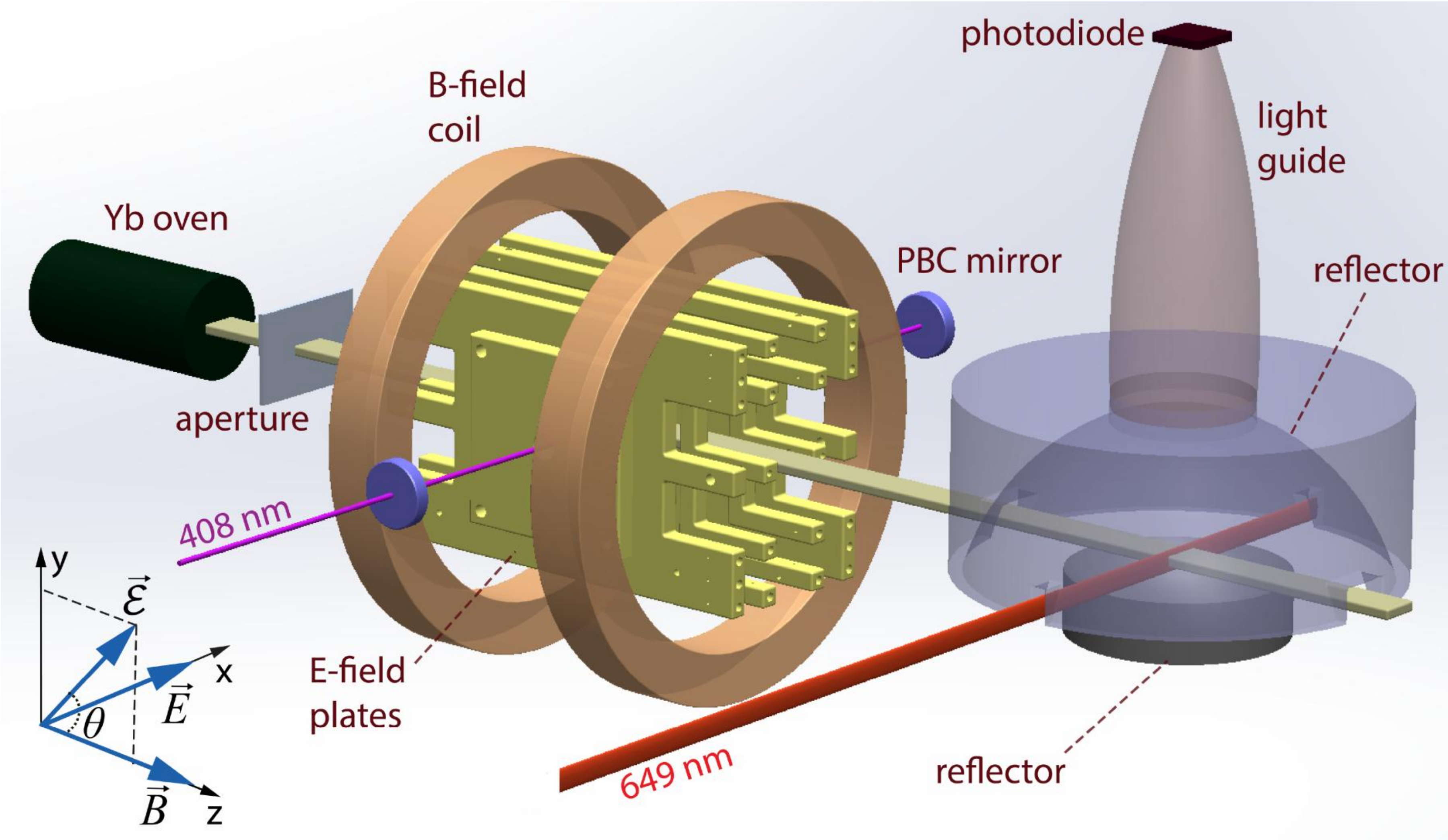
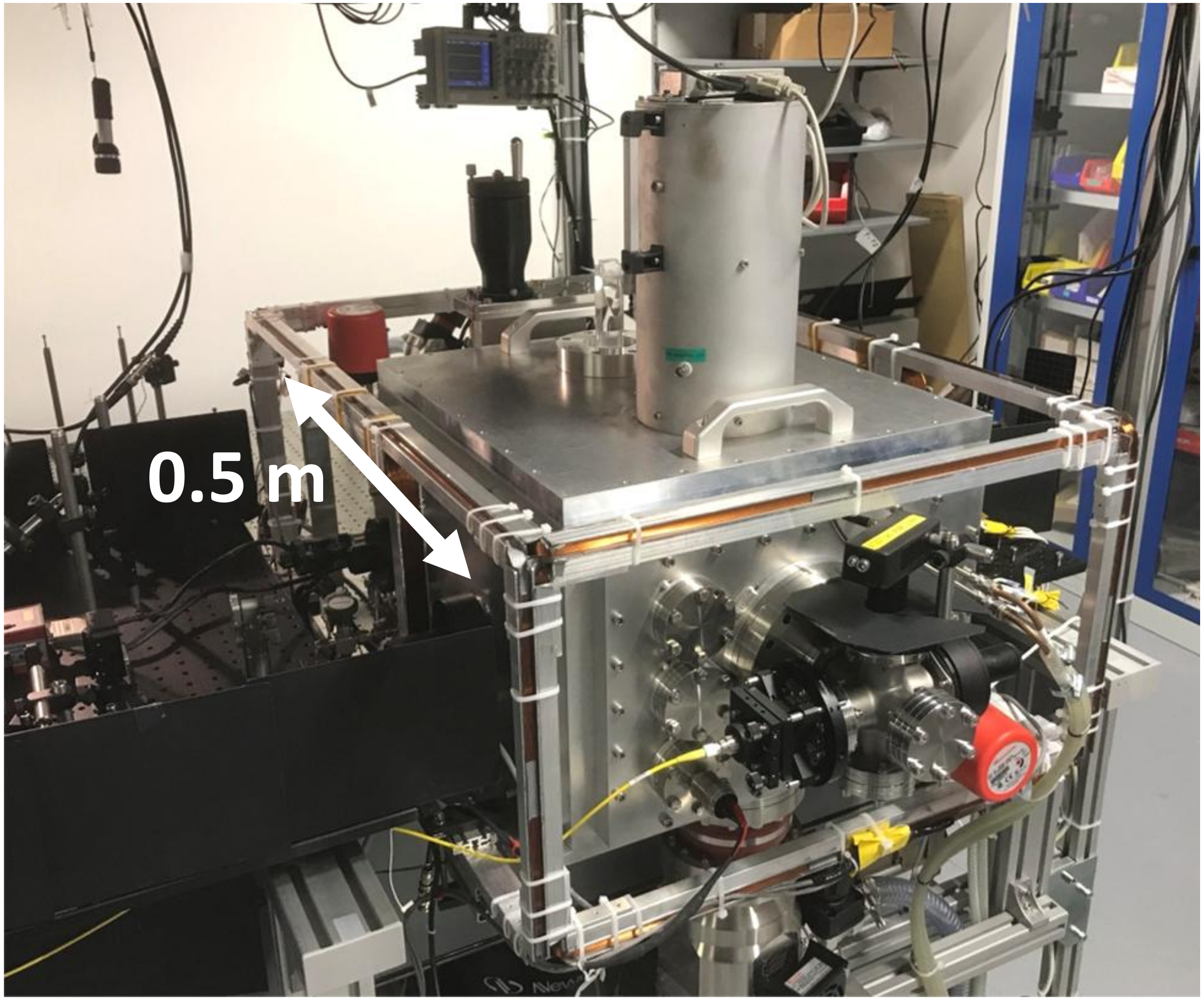
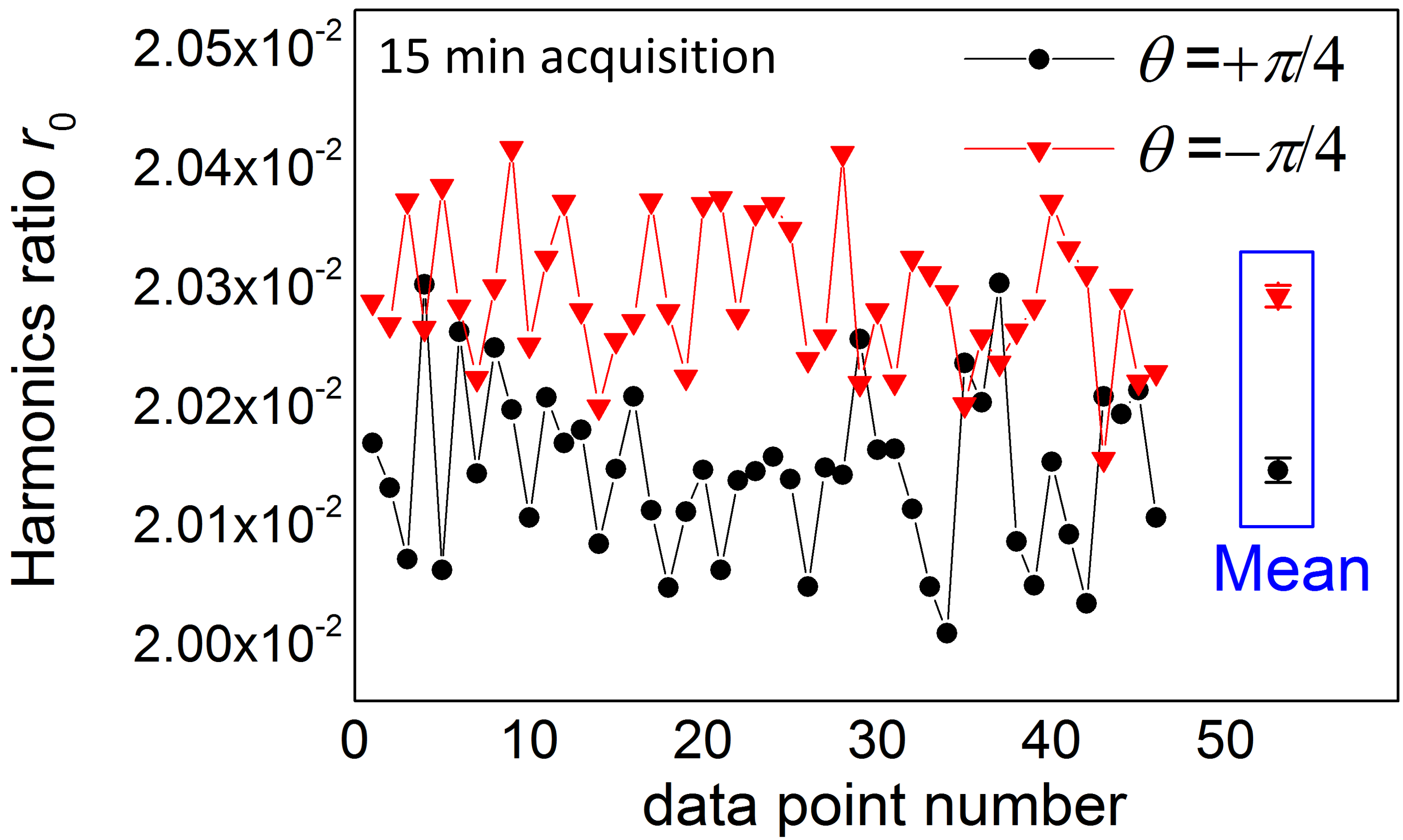
Apparatus schematic



The atomic-beam apparatus

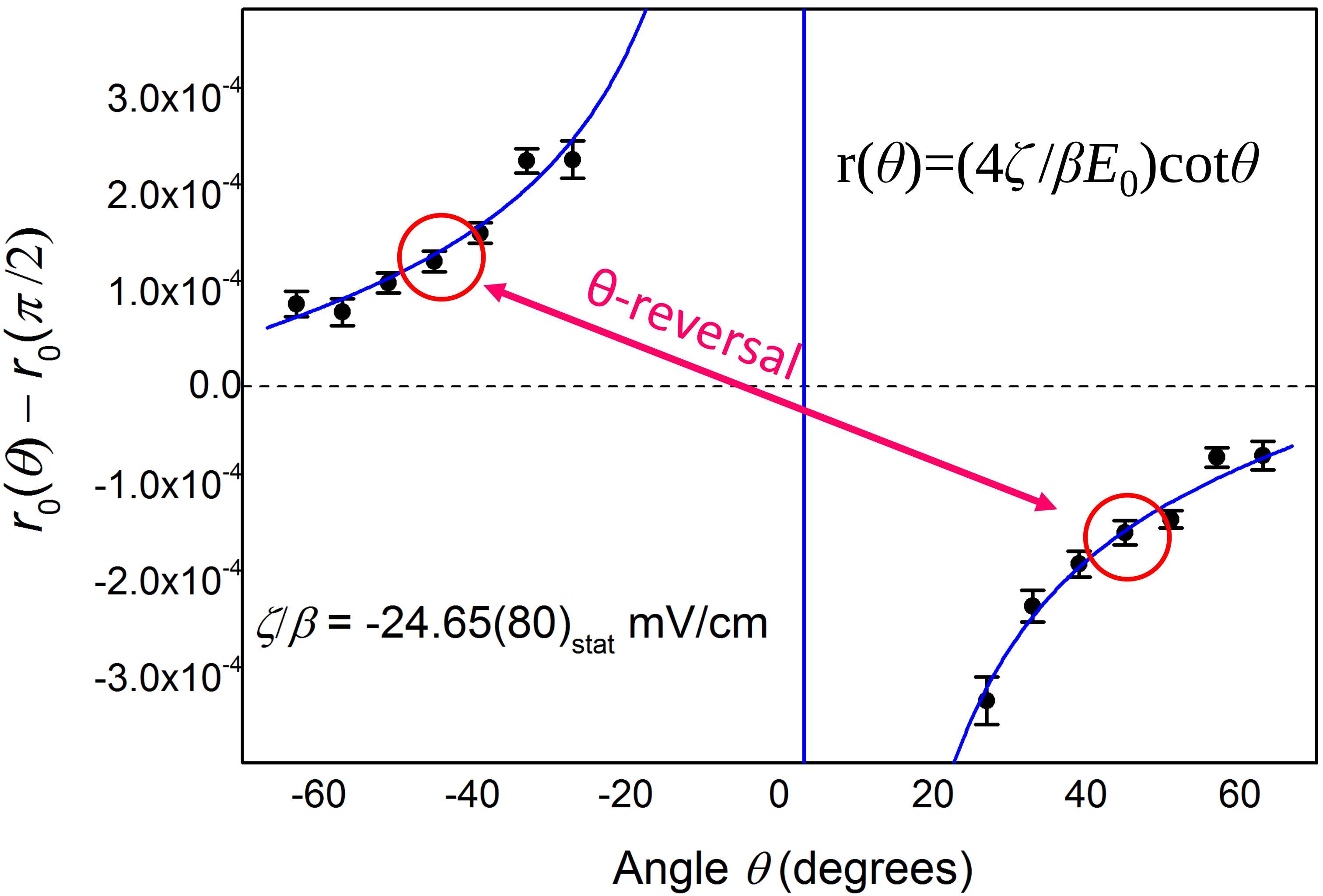


Harmonics ratio & θ-reversal



$$\text{Asymmetry} = r(\theta=\pi/4) - r(\theta=-\pi/4)$$

Mapping out the θ-dependence



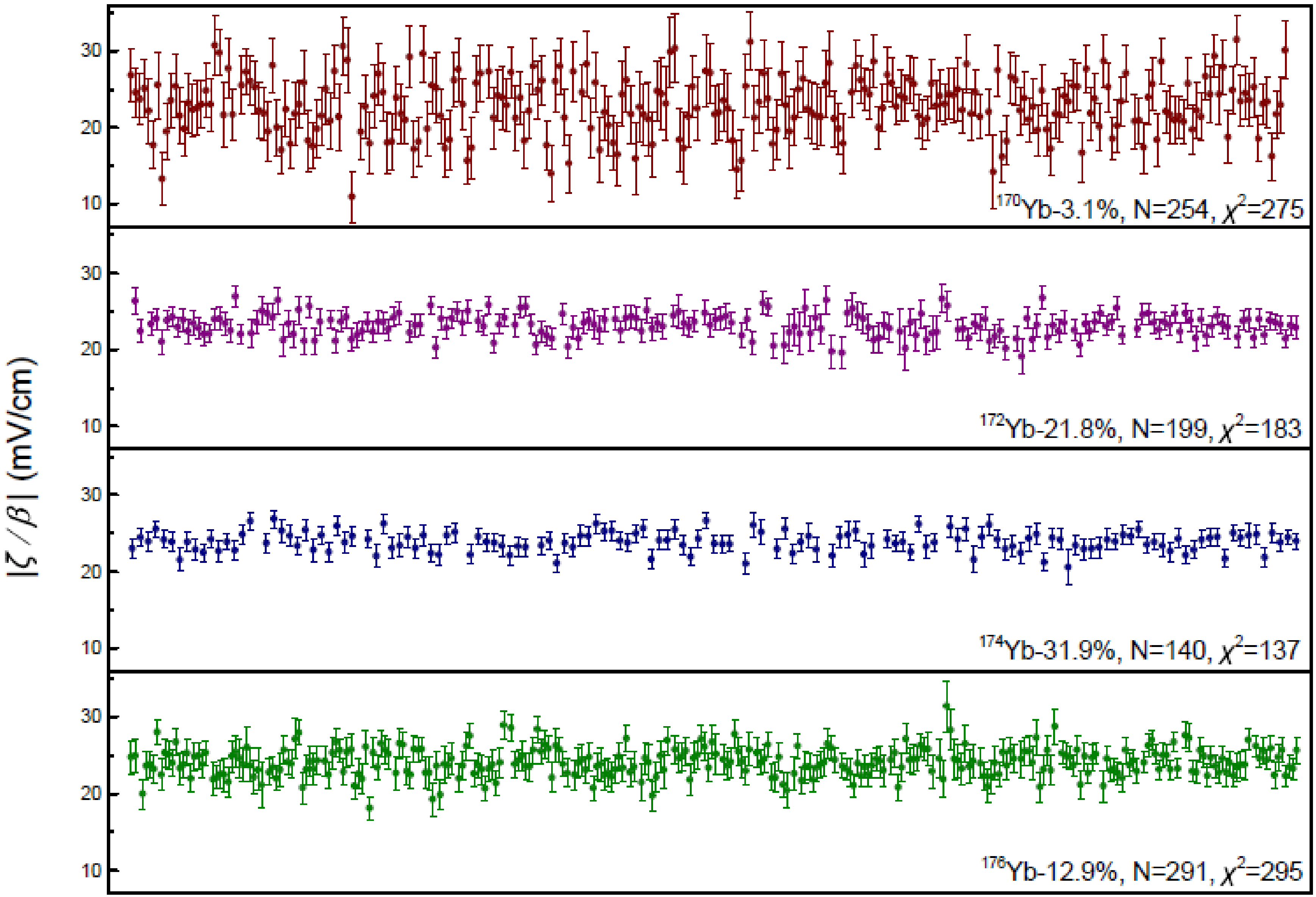
Some sanity checks

TABLE II. Results of auxiliary experiments.

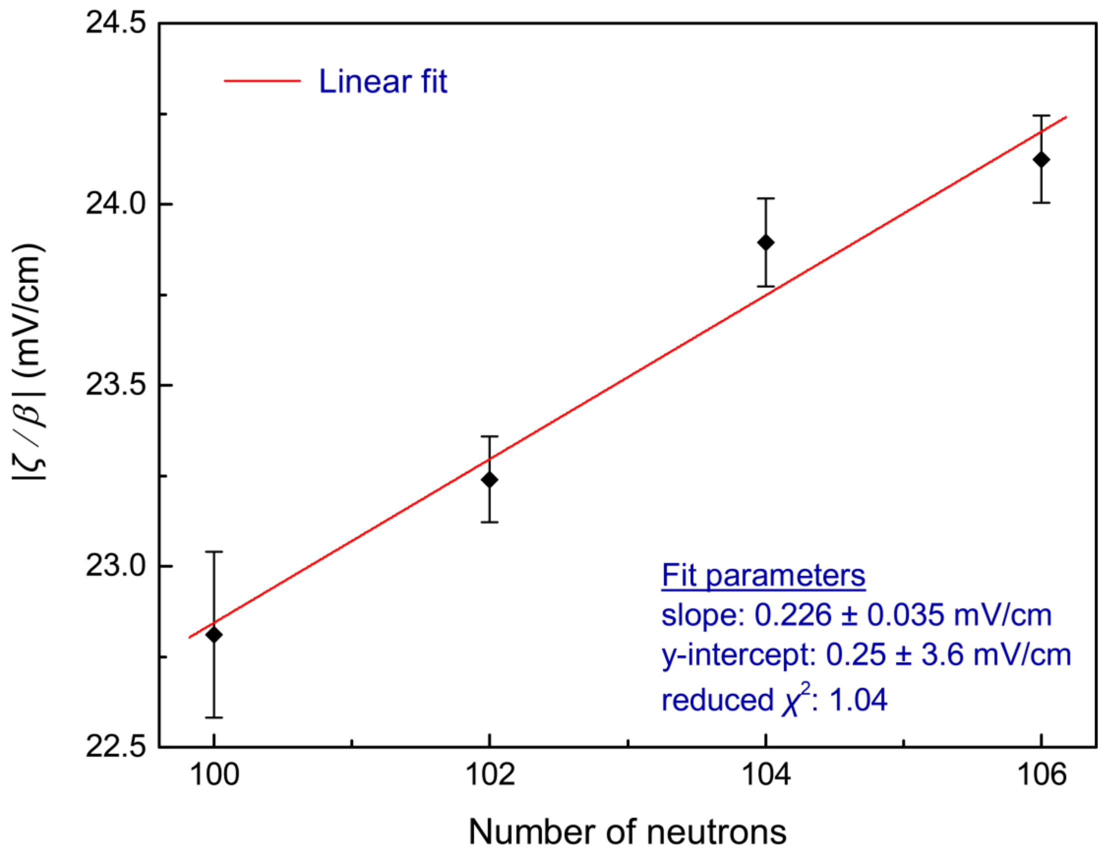
Isotope mass number	Transition	Type of experiment	ζ/β (mV/cm)
174	$m = 0 \to m' = 0$	Actual isotopic comparison data	−23.89(11)
174	$m = 0 \to m' = \pm 1$	...	23.30(26)[a]
174	$m = 0 \to m' = 0$	Measurement of r_0 vs θ[b]	−24.65(80)
174	$m = 0 \to m' = 0$	Enhanced $e_y^r/E_0 = -0.03$	−24.30(48)
174	$m = 0 \to m' = 0$	Enhanced $e_y^r/E_0 = 0.03$	−23.93(40)
174	$m = 0 \to m' = 0$	Enhanced $e_z^r/E_0 = -0.029$	−23.98(57)
174	$m = 0 \to m' = 0$	Enhanced $e_z^r/E_0 = 0.029$	−23.76(57)
174	$m = 0 \to m' = 0$	Enhanced $e_z/E_0 = -0.076$	−24.67(57)
174	$m = 0 \to m' = 0$	Enhanced $e_z/E_0 = 0.076$	−23.83(57)
174	$m = 0 \to m' = 0$	Measurement on secondary transition peak	−24.14(44)
174	$m = 0 \to m' = 0, \pm 1$	Line-shape fitting	−21(4)
171	$F = 1/2 \to F' = 1/2$	...	−0.59(57)
174	$m = 0 \to m' = 0$	408-nm excitation using circularly polarized light	−0.2(12)
174	$m = 0 \to m' = 0$	Measurement with different field plates[c]	−25.2(12)
174	$m = 0 \to m' = 0$	Measurement without PBC	−26(7)

[a]The PV-mimicking terms $e_y^r(e_z/E_0)$ and $e_z^r(e_y/E_0)$ were not compensated prior to the measurement [see Appendix A and Eq. (A24)].
[b]See Fig. 10.
[c]Done without the high degree of 408-nm polarization control implemented in the isotopic comparison runs.

2018 run in four spin-zero isotopes



First observation of isotopic variation in atomic PV



0.5% single isotope accuracy

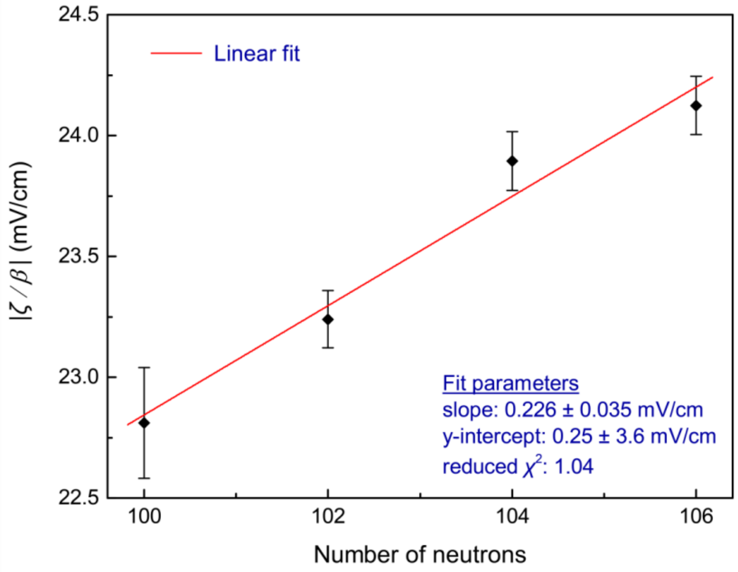
Nature Physics 15, 120 (2019)

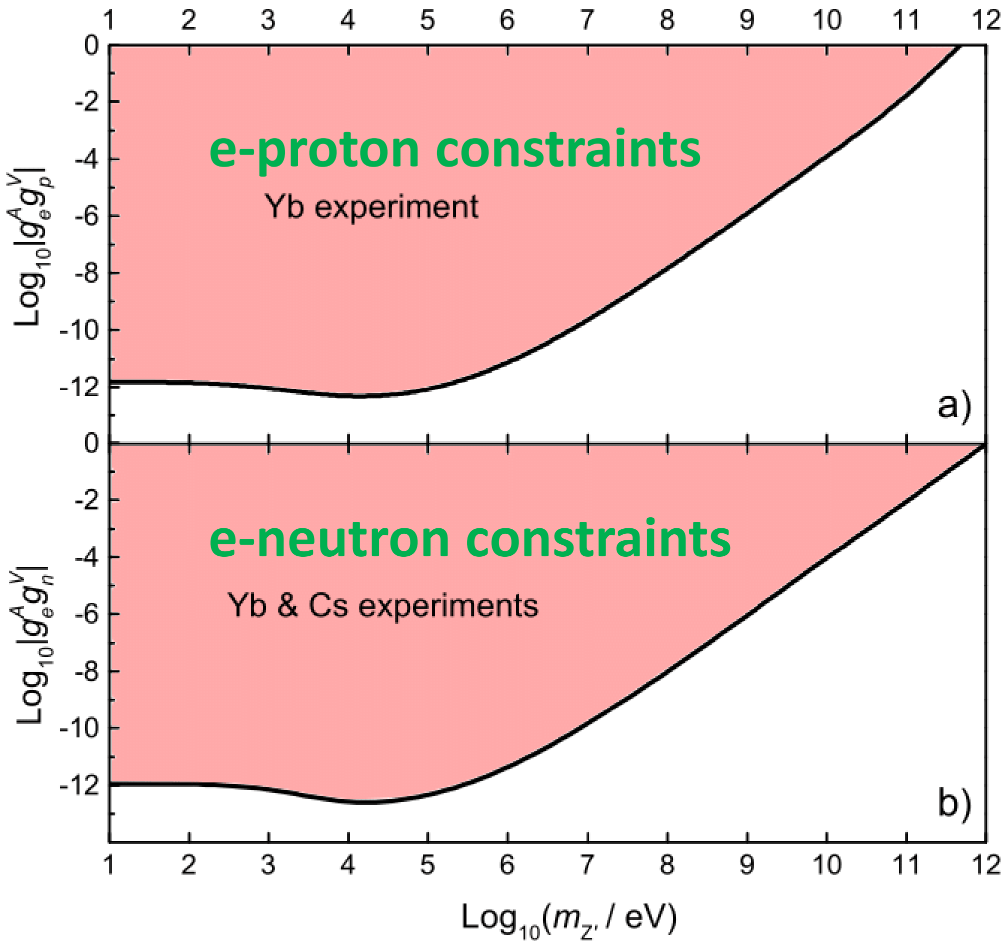
Experimental details:
PRA 100, 012503 (2019)

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

Observation: 0.96(15) % change per neutron

Constraints on light Z´-mediated e-proton & e-neutron interactions





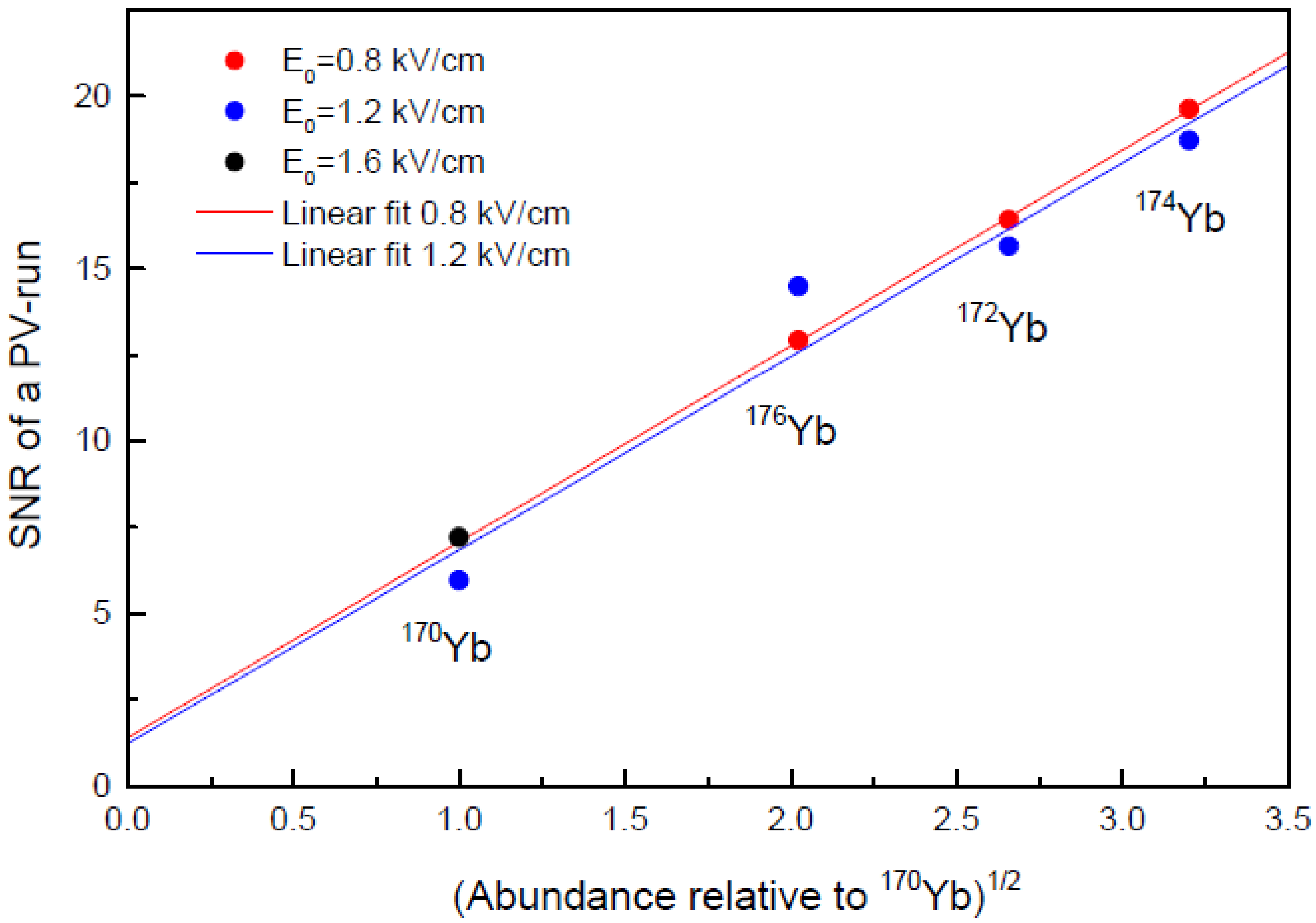
$$V_{ep(n)} = \frac{g_e^A g_{p(n)}^V}{4\pi} \frac{e^{-m_{Z'} r}}{r} \gamma_5$$

In collaboration with V. Flambaum

Dzuba, Flambaum and Stadnik, PRL 119, 223201 (2017)

Nature Physics 15, 120 (2019)

Nearly shot-noise-limited sensitivity



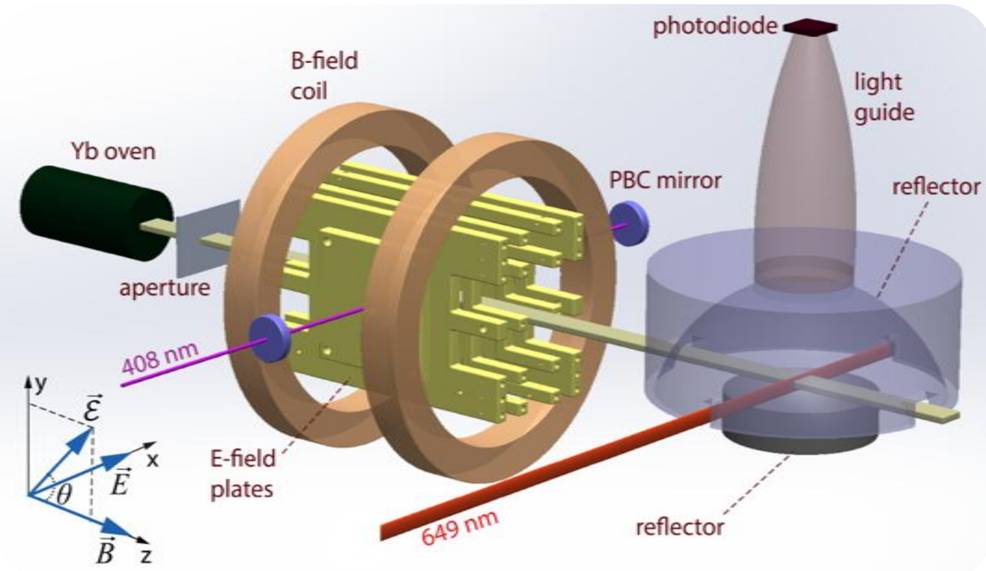
Single isotope measurement uncertainties

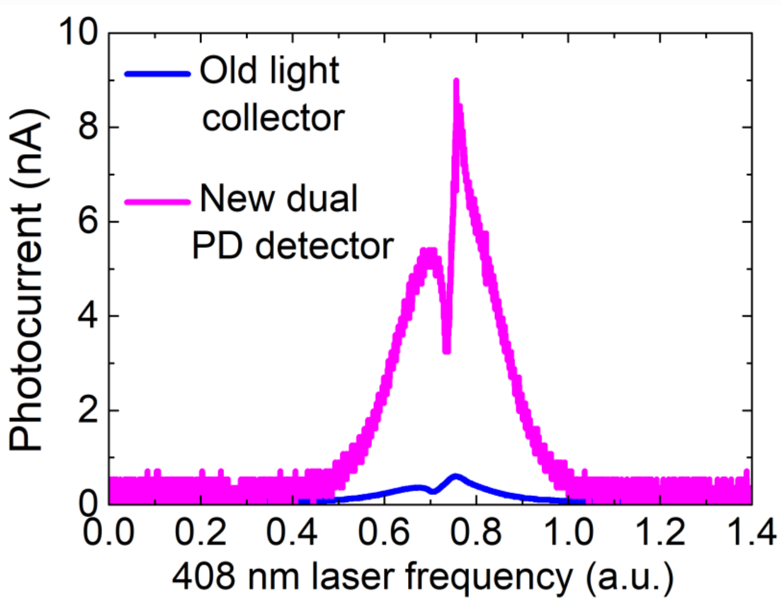
Systematic uncertainties	Contribution(%)
Harmonics ratio calibration	0.22
Polarization angle	0.1
High-voltage measurements	0.06
Transition saturation correction	0.05 (0.09 for ^{170}Yb)
Field-plate spacing	0.04
Photodetector response calibration	0.02
Stray fields & field-misalignments	0.02
Total systematic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

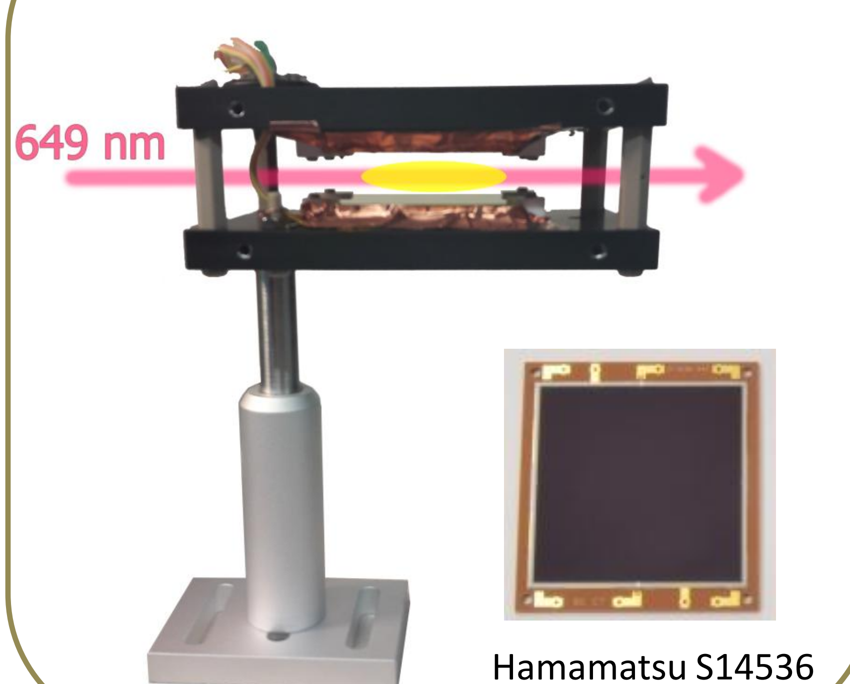
Effect comparison **bonus**:
decreased sensitivity to systematics

Progress with signal enhancement





New detector: ×2 large-area PD



Hamamatsu S14536
PIN photodiode

- ×2 wider atom beam
- New detector

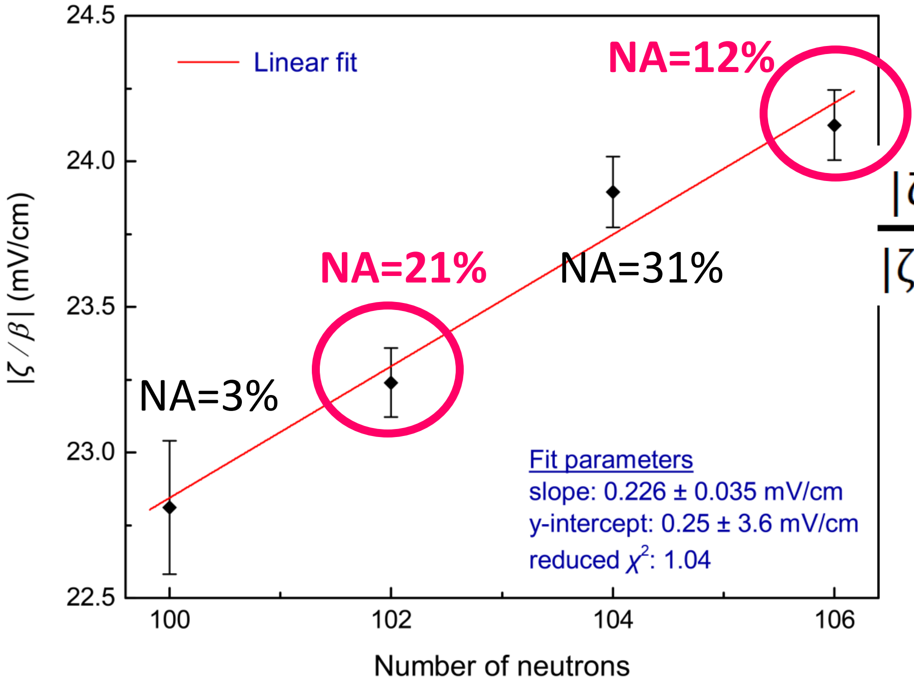
×15 larger photocurrent

Progress with signal enhancement (cont'd)

- Boost the Yb oven flux (×2 flux is stable)
- Power build-up cavity mirror upgrade

  (×2 more power with stable operation)
- Transverse-cool the atomic beam (×3 ?) Tricky
- Integrate longer….?

Next: Probing variation of Yb neutron skin



$$\frac{|\zeta/\beta|}{|\zeta/\beta|'} \approx 1 + \frac{\Delta N}{N} + \frac{3}{7}(\alpha Z)^2 \frac{[\Delta R'_{ns} - \Delta R_{ns}]}{R_p}$$

~ 0.09% (Yb -172 & Yb-176)

Brown, Derevianko, Flambaum
PRC C79, 035501 (2009)

- 2018 Run: a total 200 hr to measure each of Yb-172 and Yb-176 to 0.4%
- ×60 signal enhancement: 0.05% uncertainty in ratio in 475 hr

Next: spin-dependent PV and anapole moment

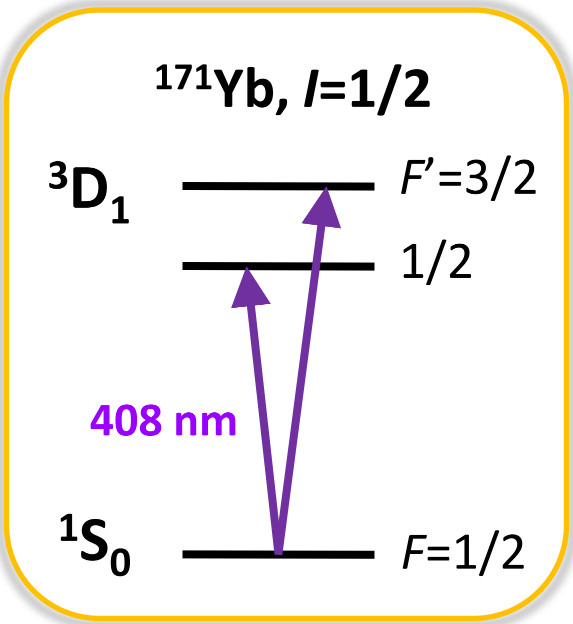


TABLE II. PNC amplitudes (z components) for the $|6s^2, {}^1S_0, F_1\rangle \rightarrow |6s5d, {}^3D_1, F_2\rangle$ transitions in ^{171}Yb and ^{173}Yb in units of $E'Q_W$ and $10^{-9} iea_0$.

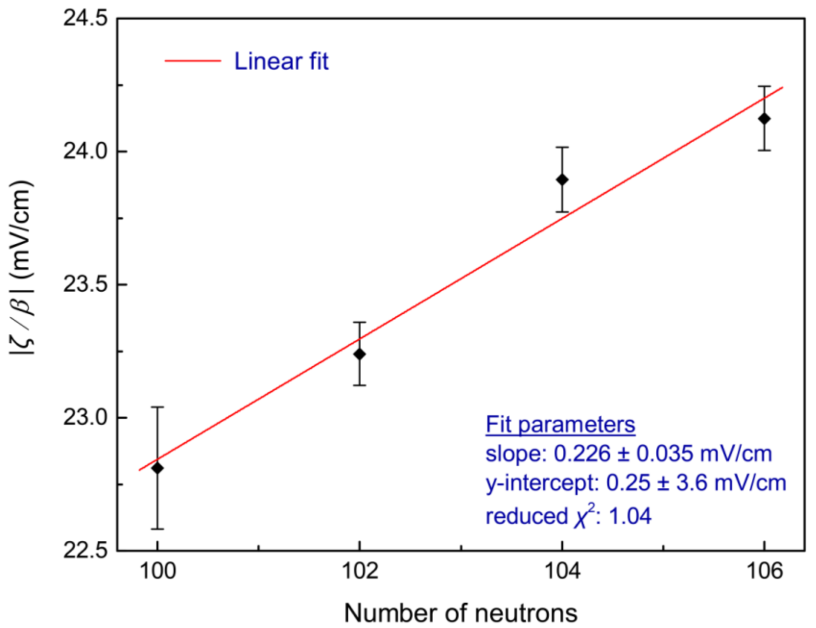
				PNC amplitude	
A	I	F_1	F_2	units: $E'Q_W$	units: $10^{-9} iea_0$
171	0.5	0.5	0.5	$-(1/3)(1-0.0161\varkappa)$	$6.15(1-0.0161\varkappa)$
		0.5	1.5	$\sqrt{2/9}(1+0.0081\varkappa)$	$-8.70(1+0.0081\varkappa)$
173	2.5	2.5	1.5	$-\sqrt{4/45}(1-0.0111\varkappa)$	$5.61(1-0.0111\varkappa)$
		2.5	2.5	$-\sqrt{5/21}(1-0.0032\varkappa)$	$9.18(1-0.0032\varkappa)$
		2.5	3.5	$\sqrt{2/21}(1+0.0079\varkappa)$	$-5.81(1+0.0079\varkappa)$

Dzuba &Flambaum, PRA 83, 042514 (2011)

- "Best guess" PV difference between ^{171}Yb F'=3/2 and F'=1/2 ~ 0.1%
- Systematics don't necessarily cancel out in PV effect difference

Summary

- Measured PV on a chain of Yb isotopes
- 0.5% accuracy per isotope
- Constrained light Z'-mediated e-nucleon couplings
- Next: precision isotopic comparison & neutron skins



A. Frabricant

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