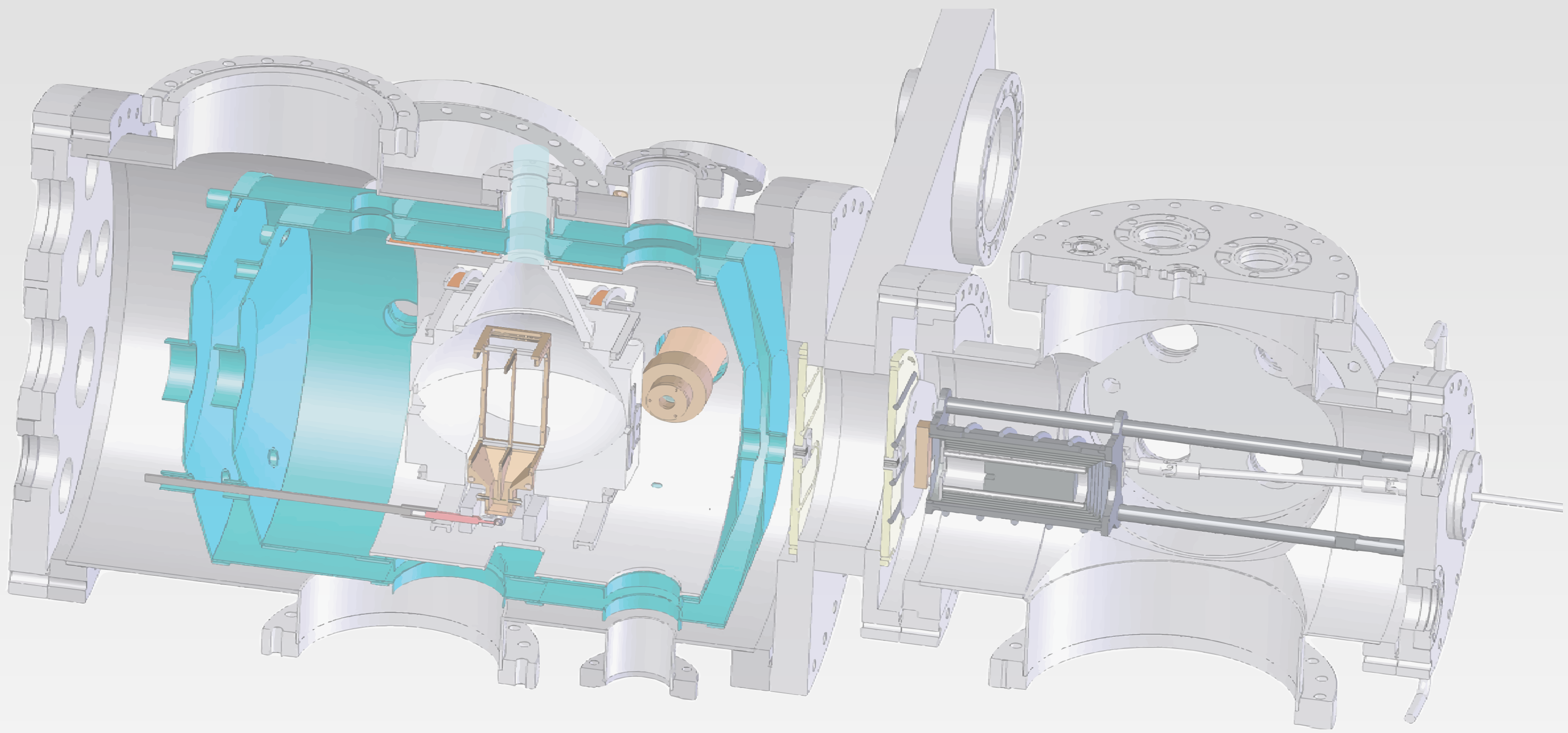
# Atomic Parity Violation in Dy

# Past, Present & Future



Lykourgos Bougas

25.05.2016 mitp



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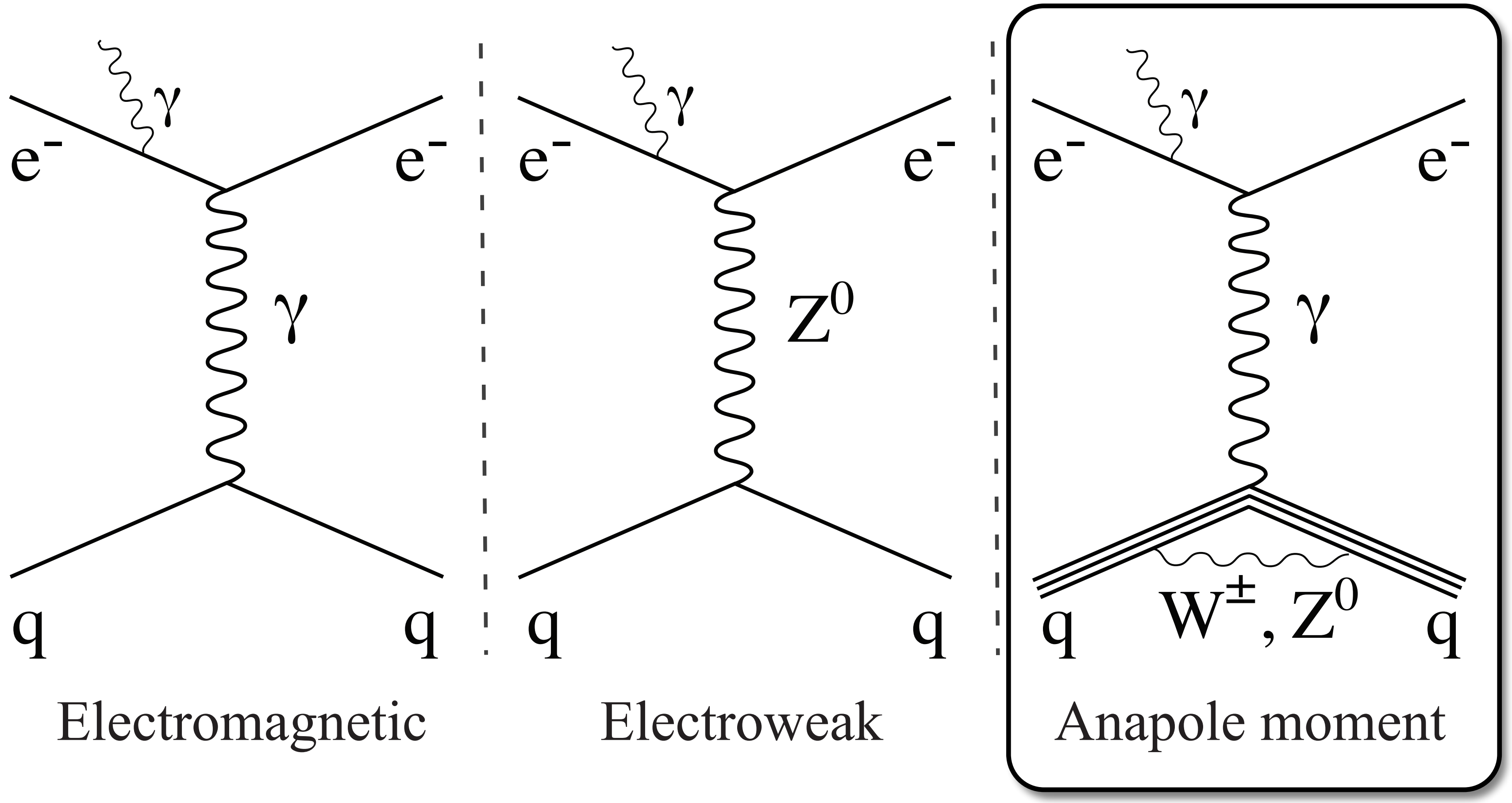
# APV in Dy

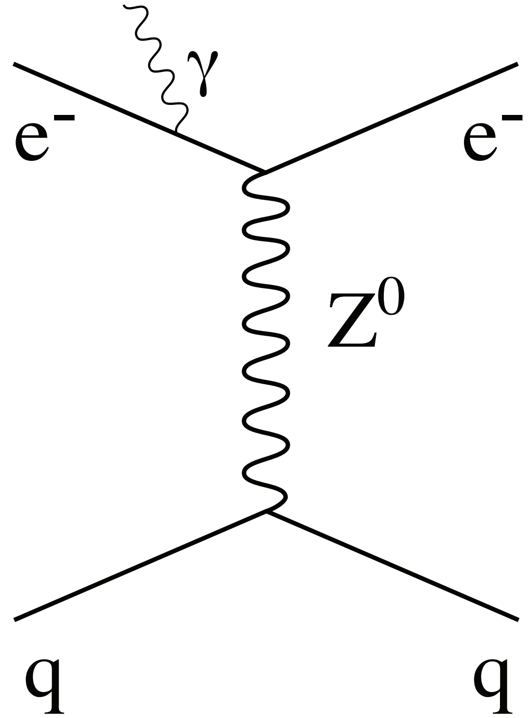



Parity
Conserving

Parity
NON-Conserving

# APV in Dy

$$H_{\mathrm{W}} = \frac{G_F}{\sqrt{2}} \frac{1}{2m_e c\hbar} Q_{\mathrm{W}} [\vec{s}\cdot\vec{p}\,\delta^3(\vec{r}) + \delta^3(\vec{r})\,\vec{s}\cdot\vec{p}]$$




**Weak interaction mixes *s* and *p* states**

$$|ns\rangle \rightarrow |ns\rangle + \delta_{\mathrm{W}} |n'p\rangle,$$

$$\delta_{\mathrm{W}} = \frac{\langle n'p|H_{\mathrm{W}}|ns\rangle}{\Delta E}$$

Bouchiat & Bouchiat (1974): $\langle n'p|H_{\mathrm{W}}|ns\rangle \sim \boldsymbol{Z}^{\mathbf{3}}$

⇩

Detectable PNC signals in high-Z atoms



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# APV 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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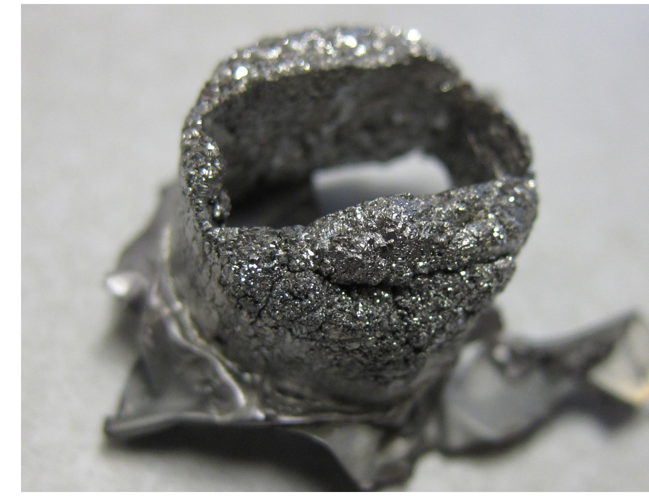

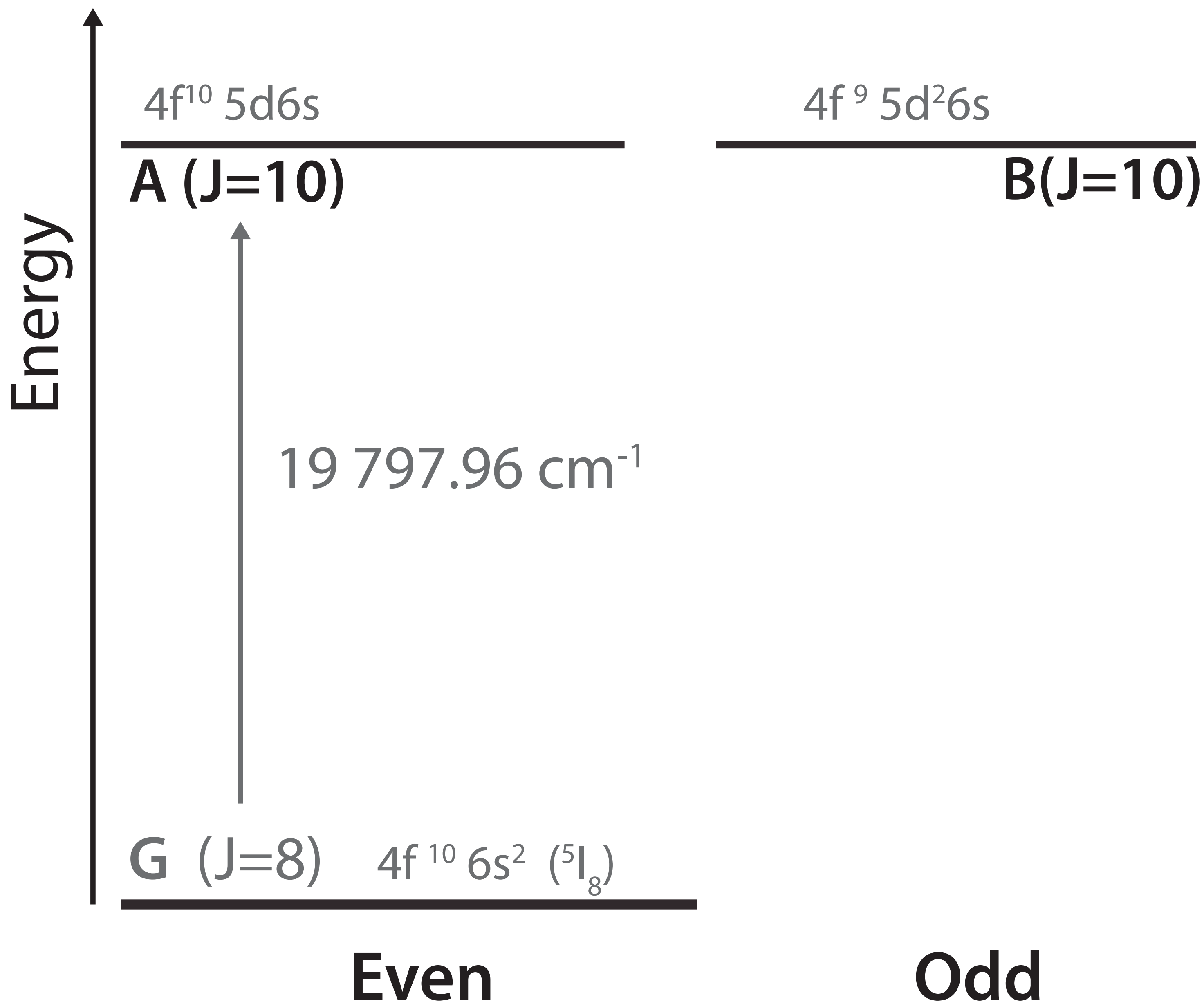

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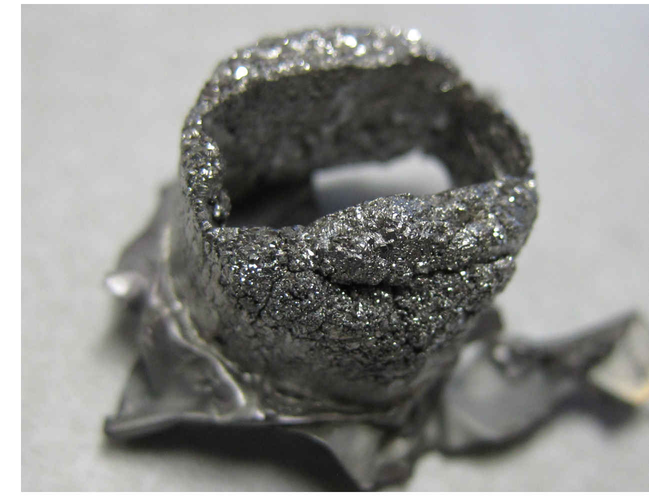

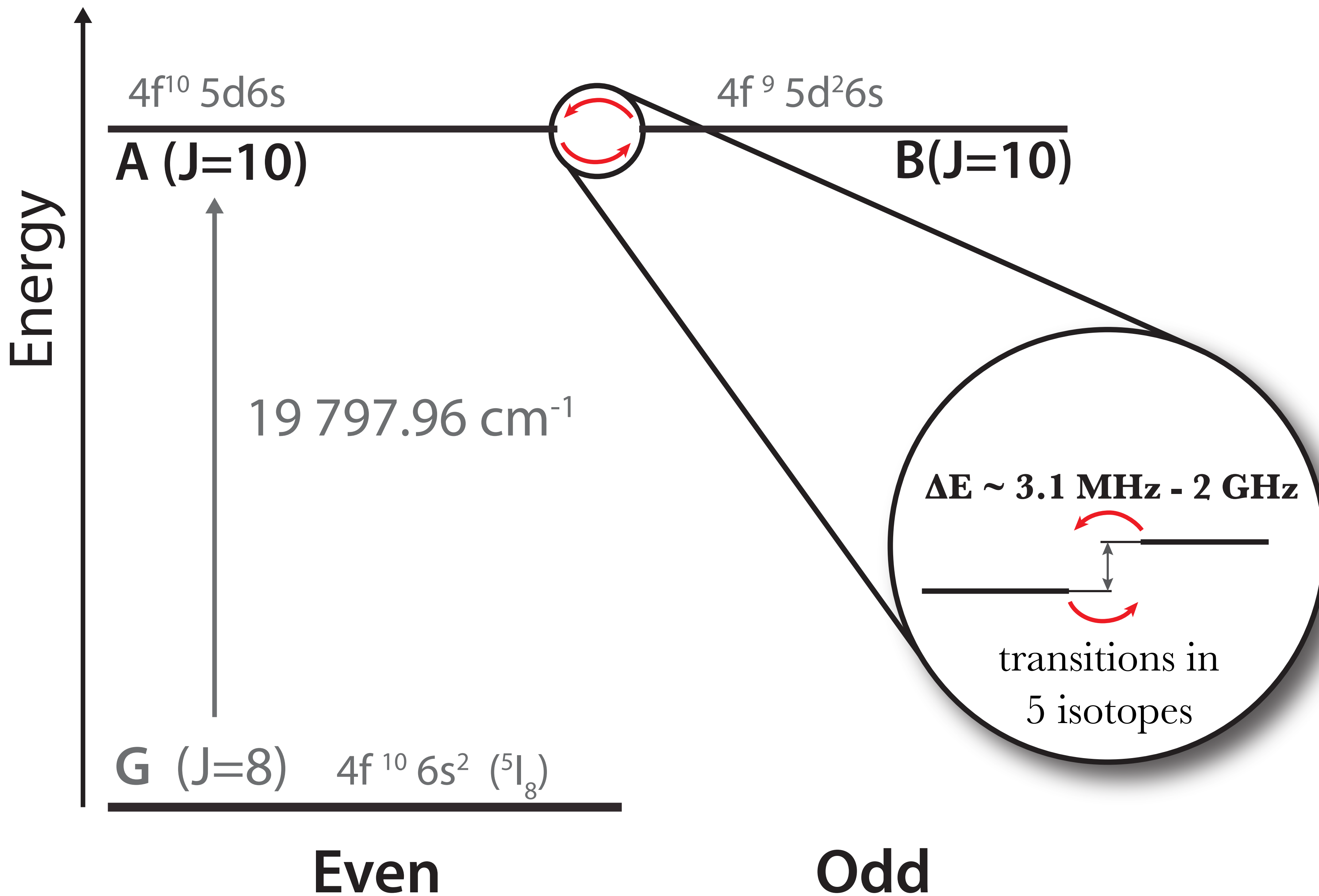

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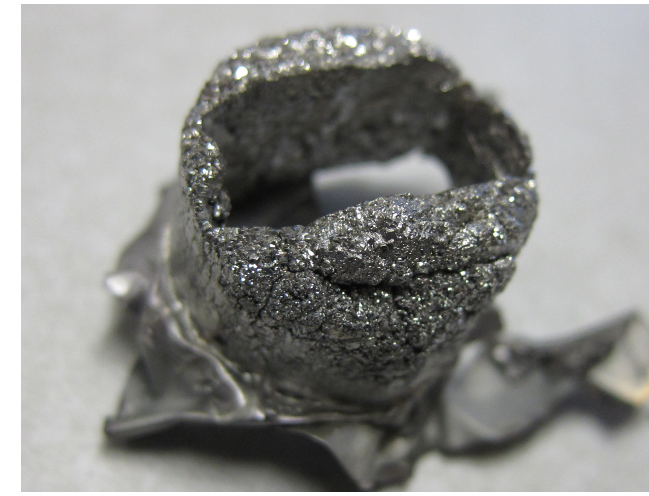
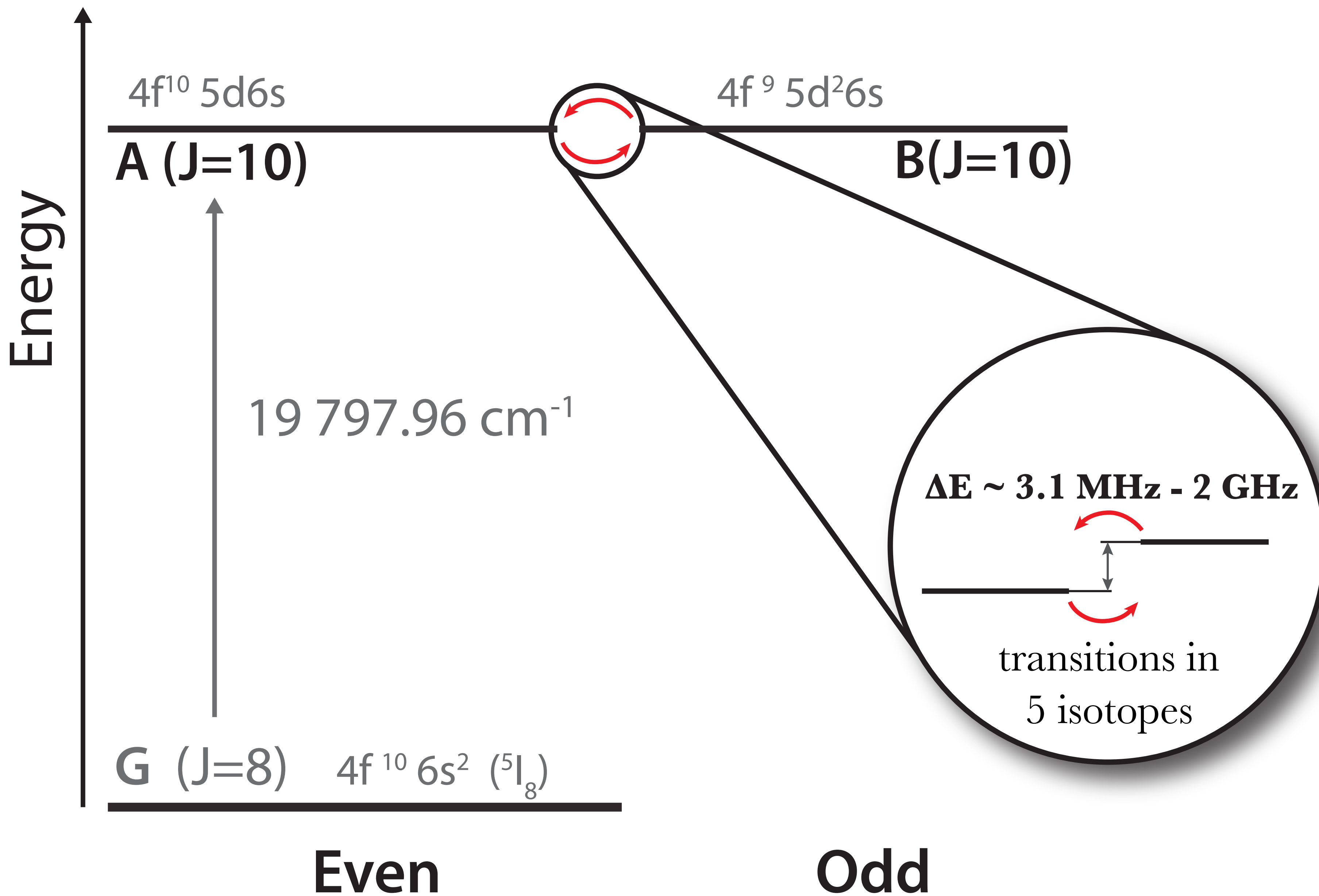


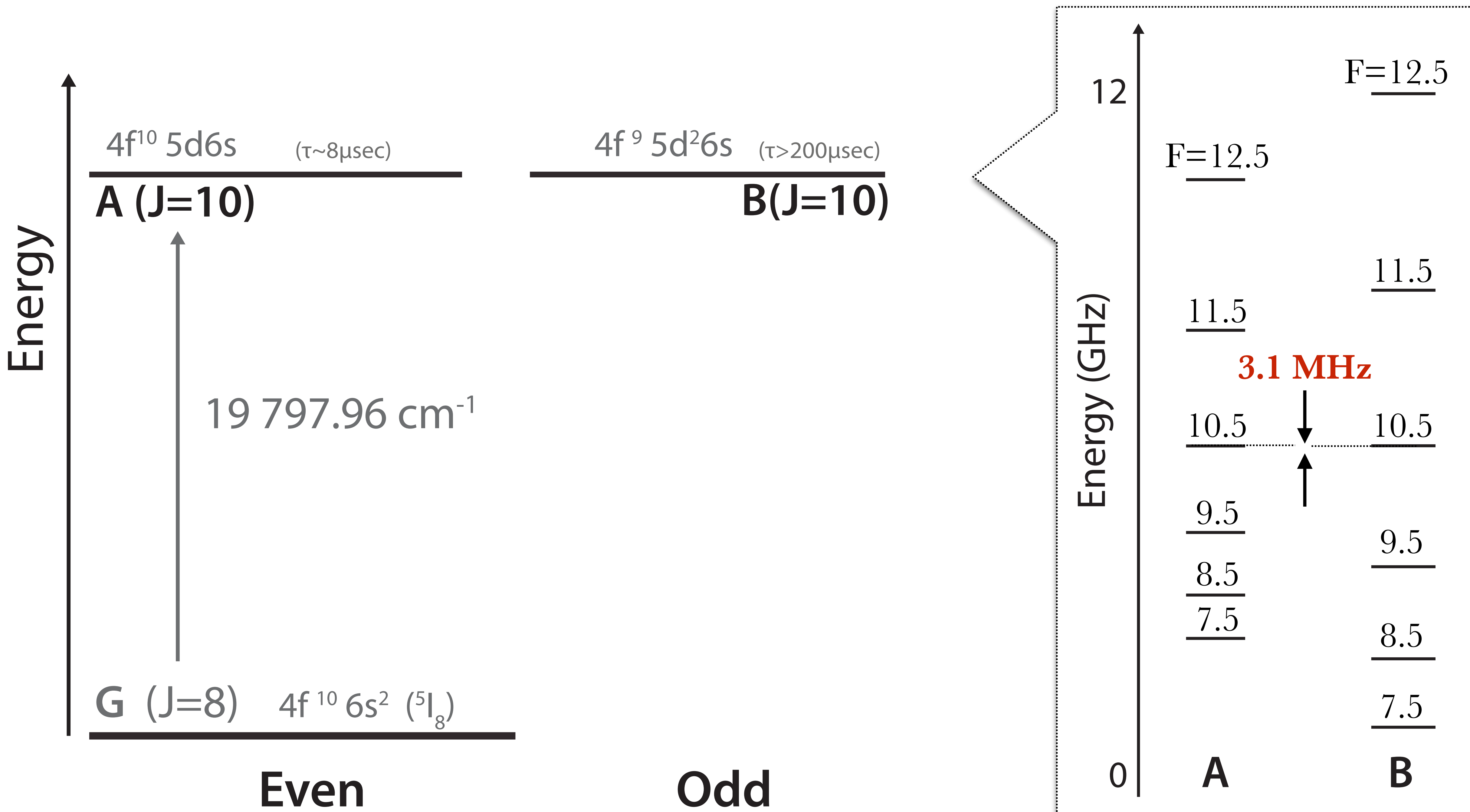



$$\delta_W = \frac{\langle n'p|H_W|ns\rangle \sim Z^3}{\Delta E}$$

Ideal APV amplifier

# APV in $^{163}$Dy

# Experiment



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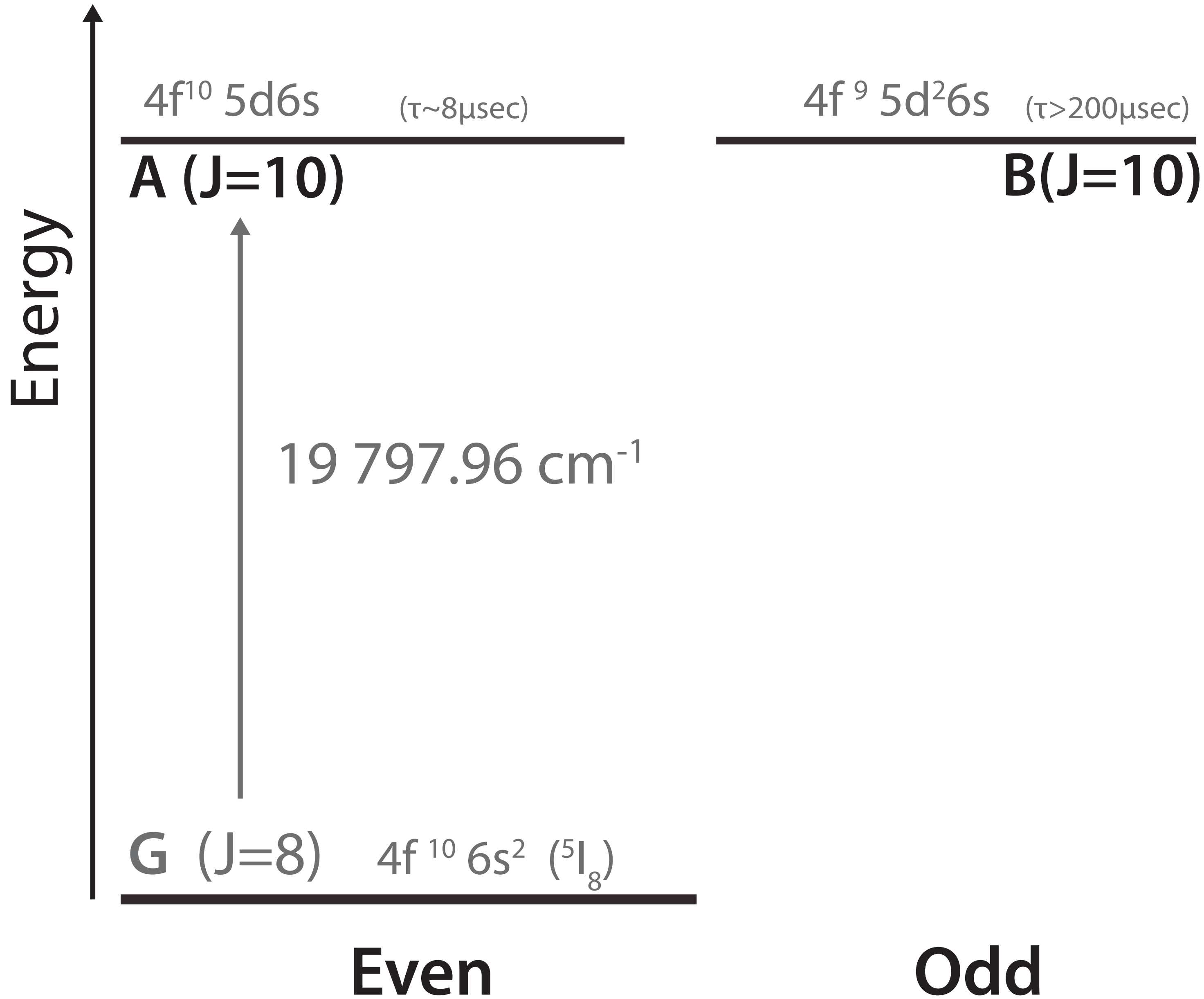
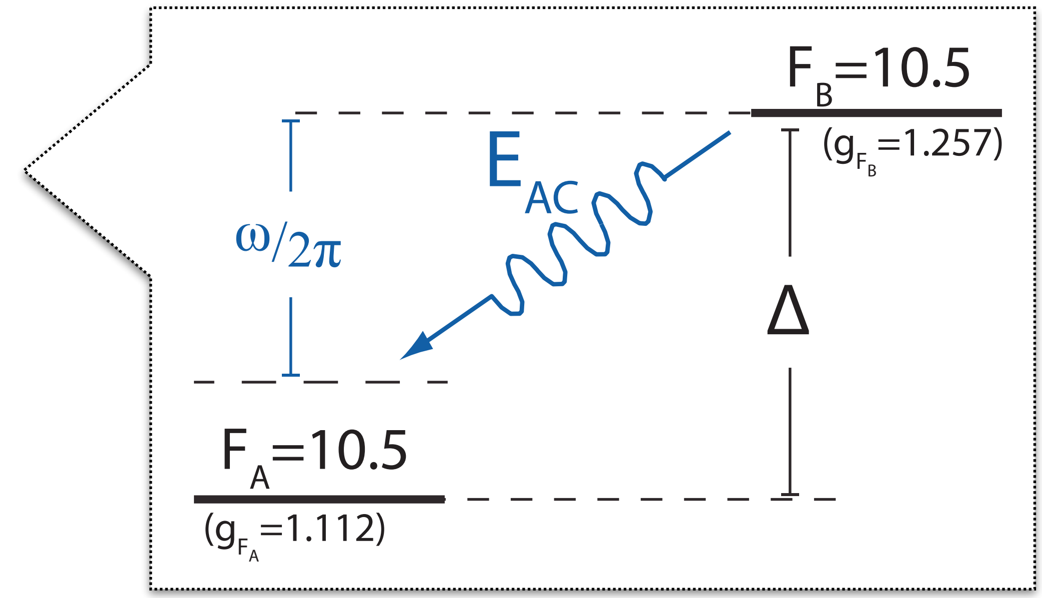
# Stark-Interference technique




## Allowed E1-PNC interference!

$$\begin{pmatrix} i\gamma/2 & iH_{\mathrm{W}} + dE_{\mathrm{AC}}\cos\omega t \\ -iH_{\mathrm{W}} + dE_{\mathrm{AC}}\cos\omega t & \Delta \end{pmatrix}$$

**Theory (1994)**

$|H_W|$=70 ± 40Hz

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



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Zeeman Crossing Spectroscopy

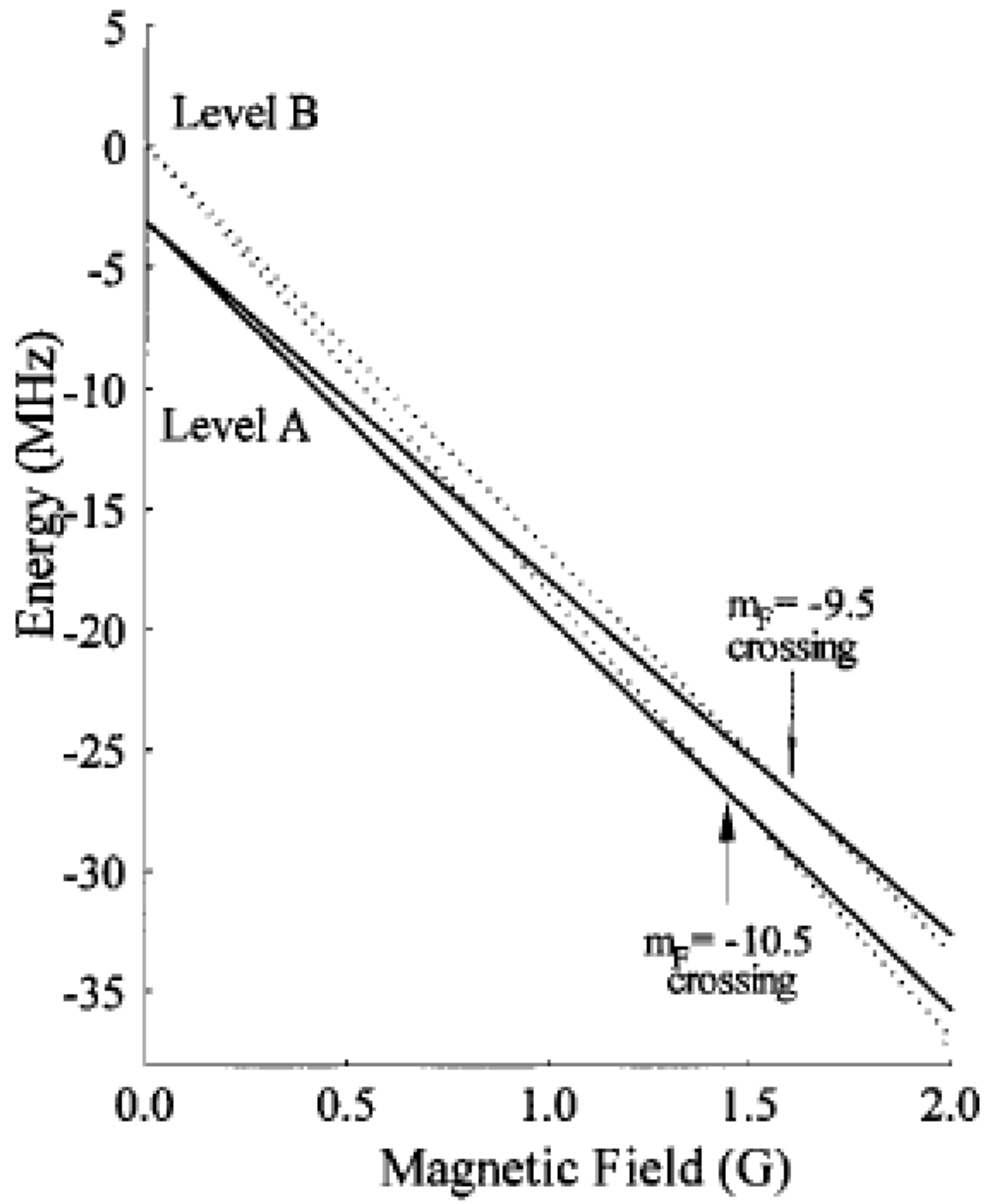
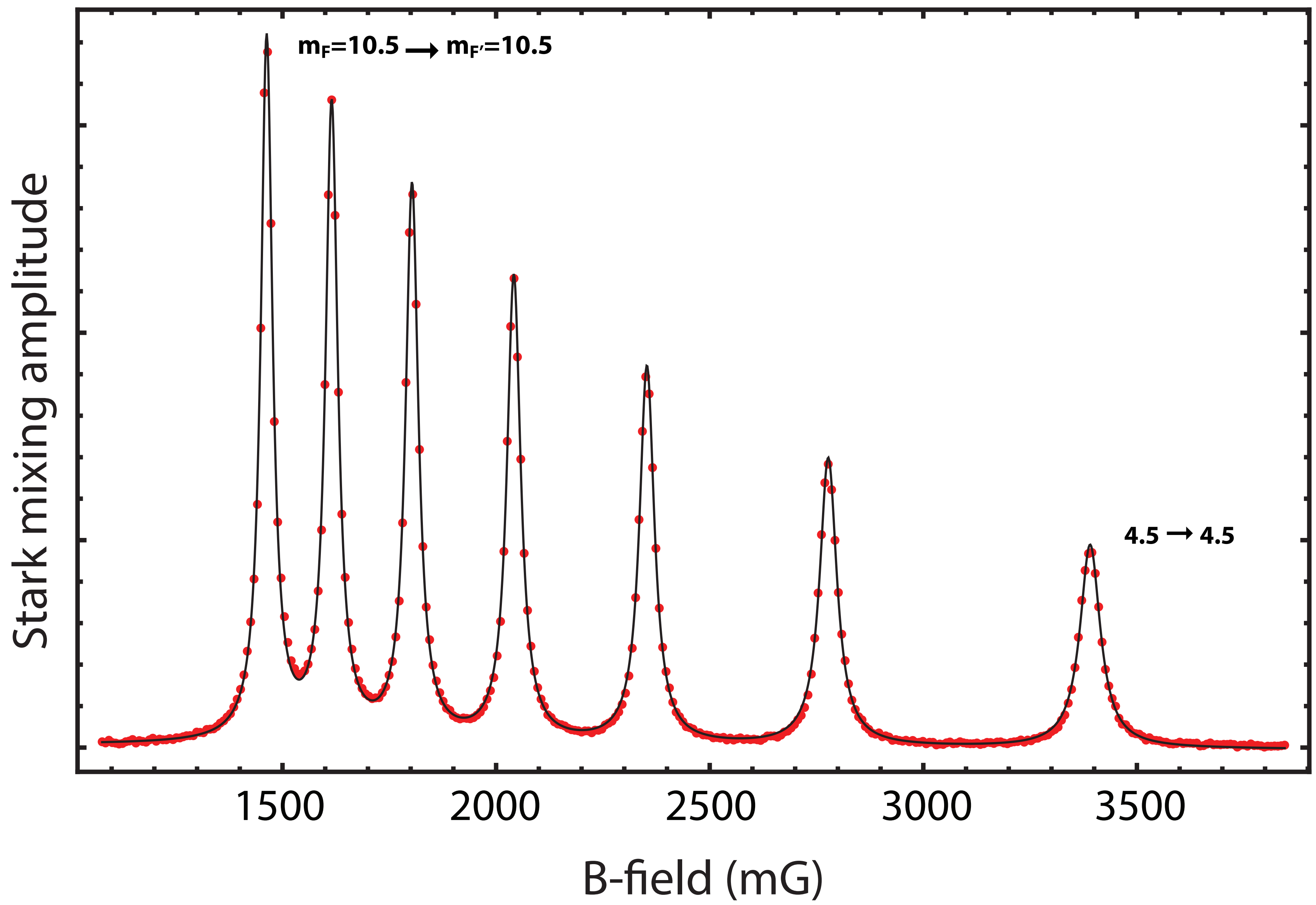



FIG. 3. Partial Zeeman structure of $^{163}$Dy $F = 10.5$ sublevels of $A$ and $B$. Zero energy is chosen arbitrarily.

# Experiment

Zeeman Crossing Spectroscopy



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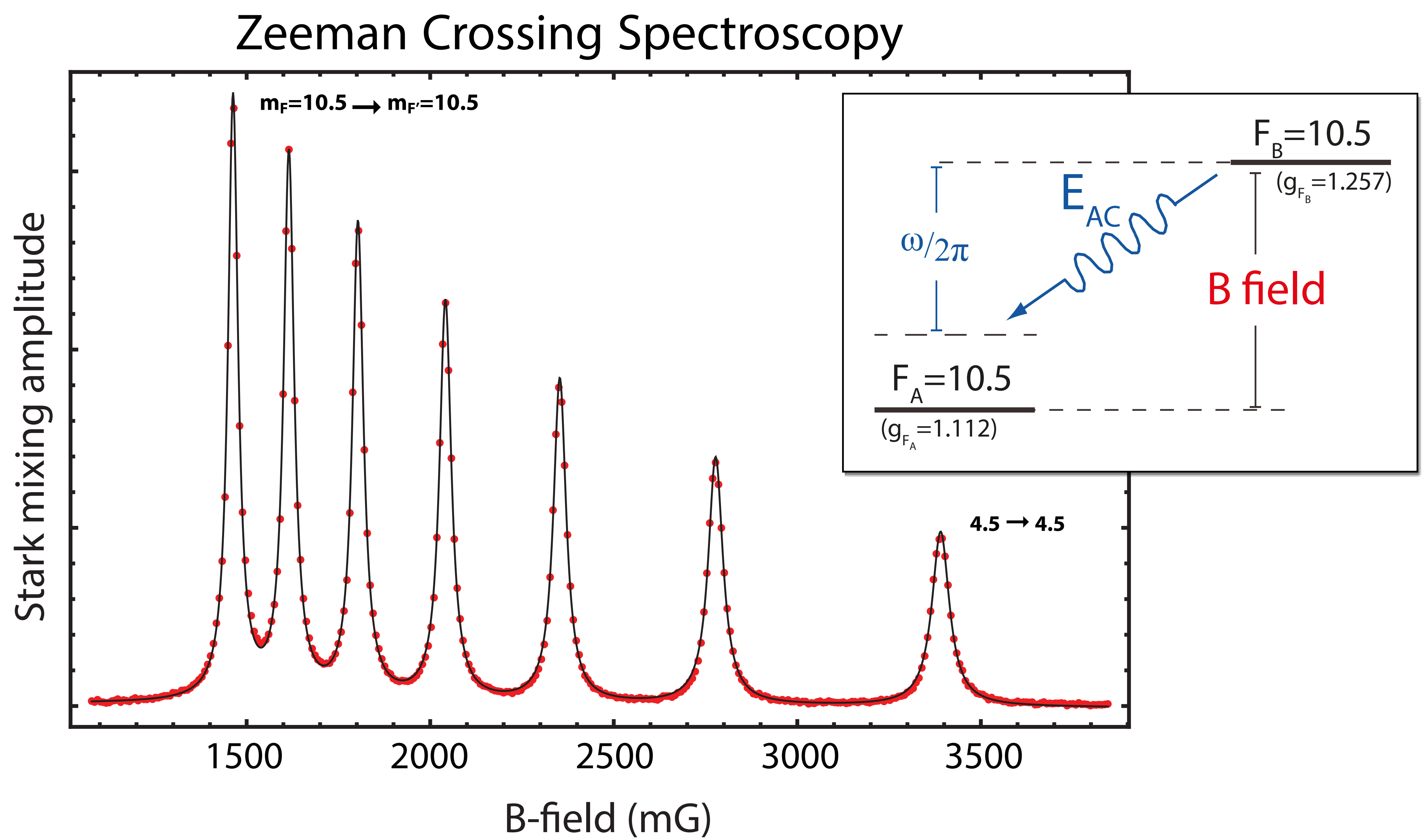
# APV in $^{163}$Dy

# Experiment




**E1-PNC interference**
**(P-odd, T-even invariant)** : $\dot{E} \cdot (B - B_{crossing})$



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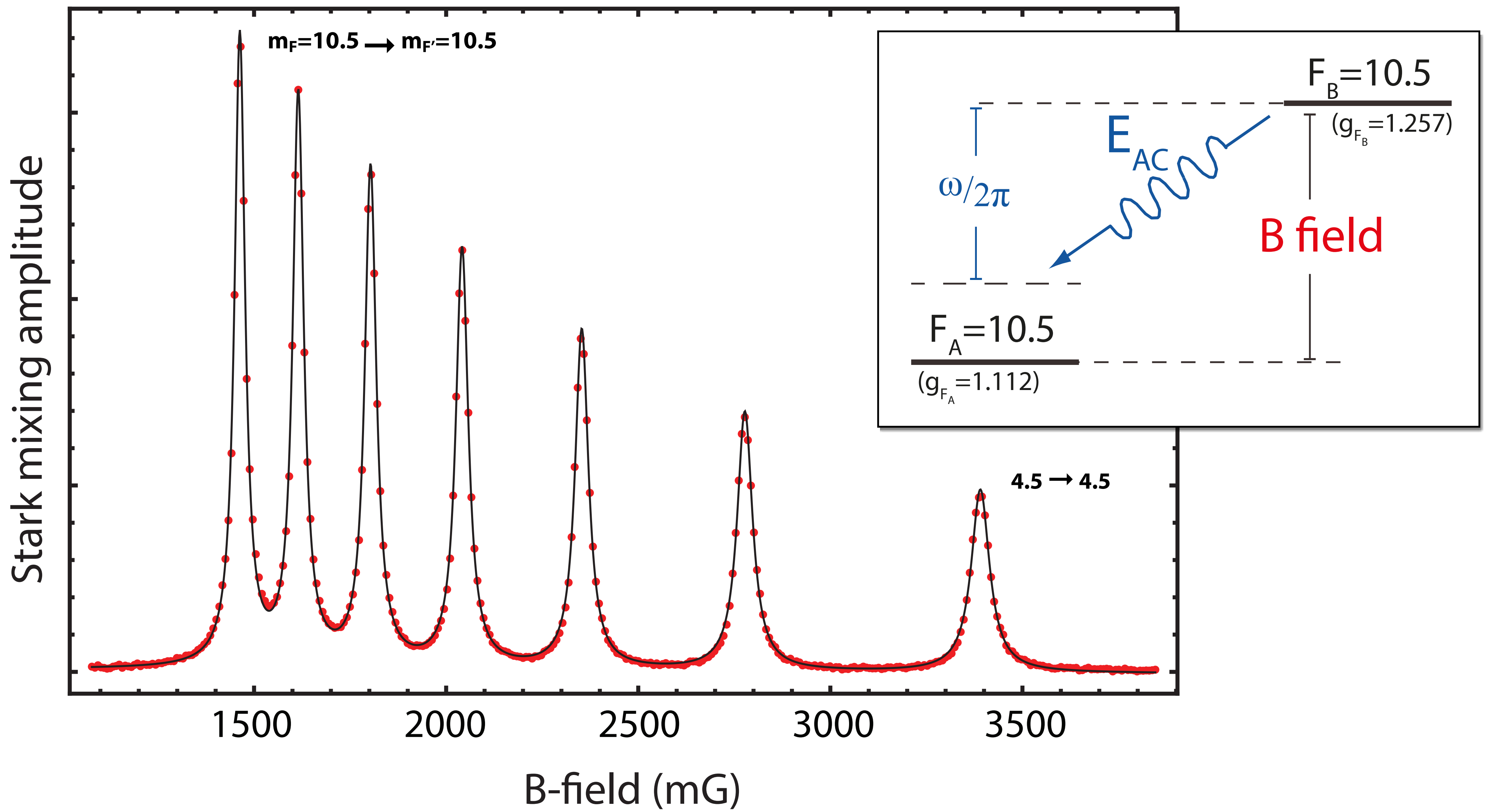
## Zeeman Crossing Spectroscopy

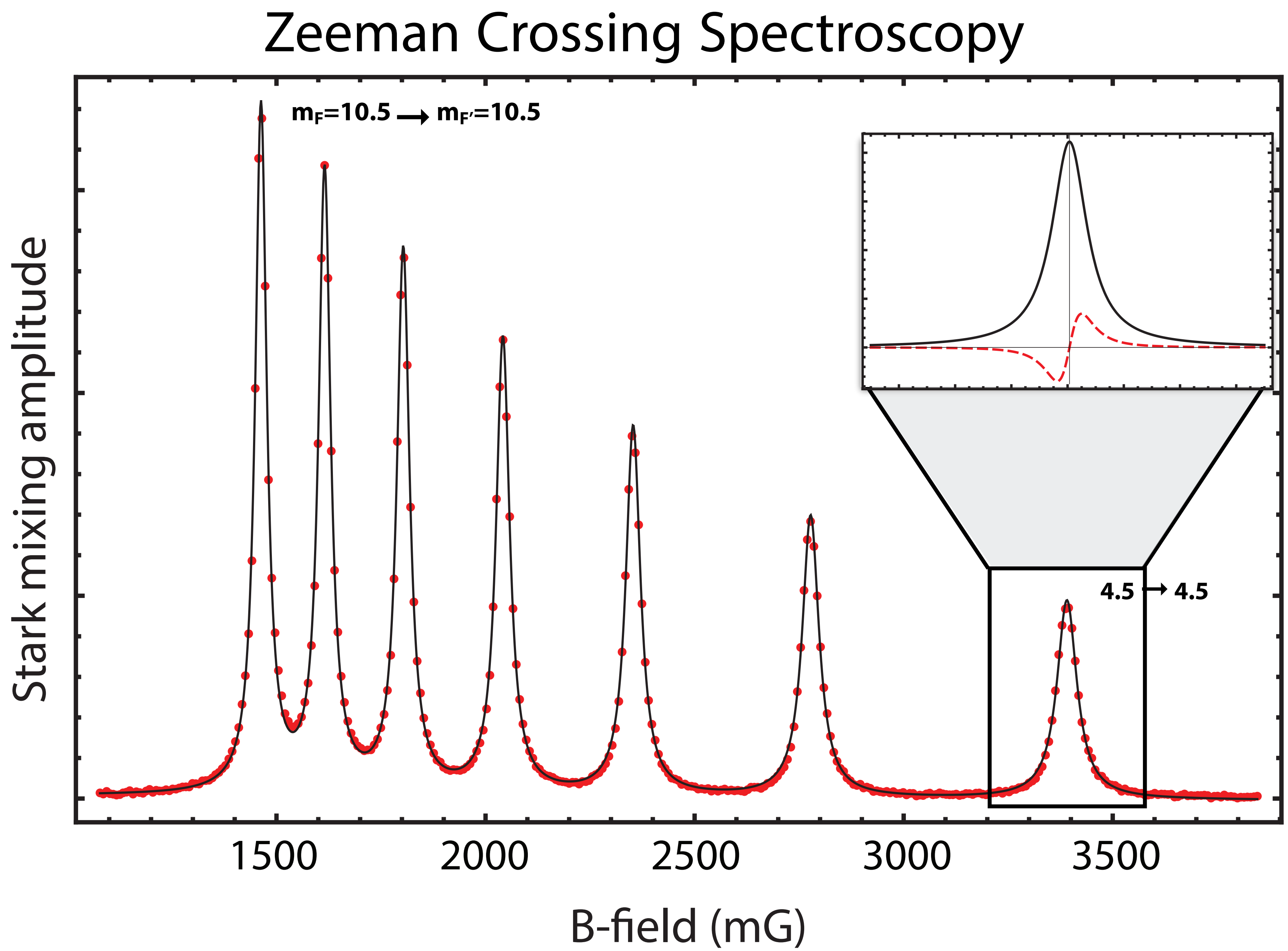



**Reversals**

- Detuning
- Magnetic field
- Electric field

# APV in $^{163}$Dy

## Experiment



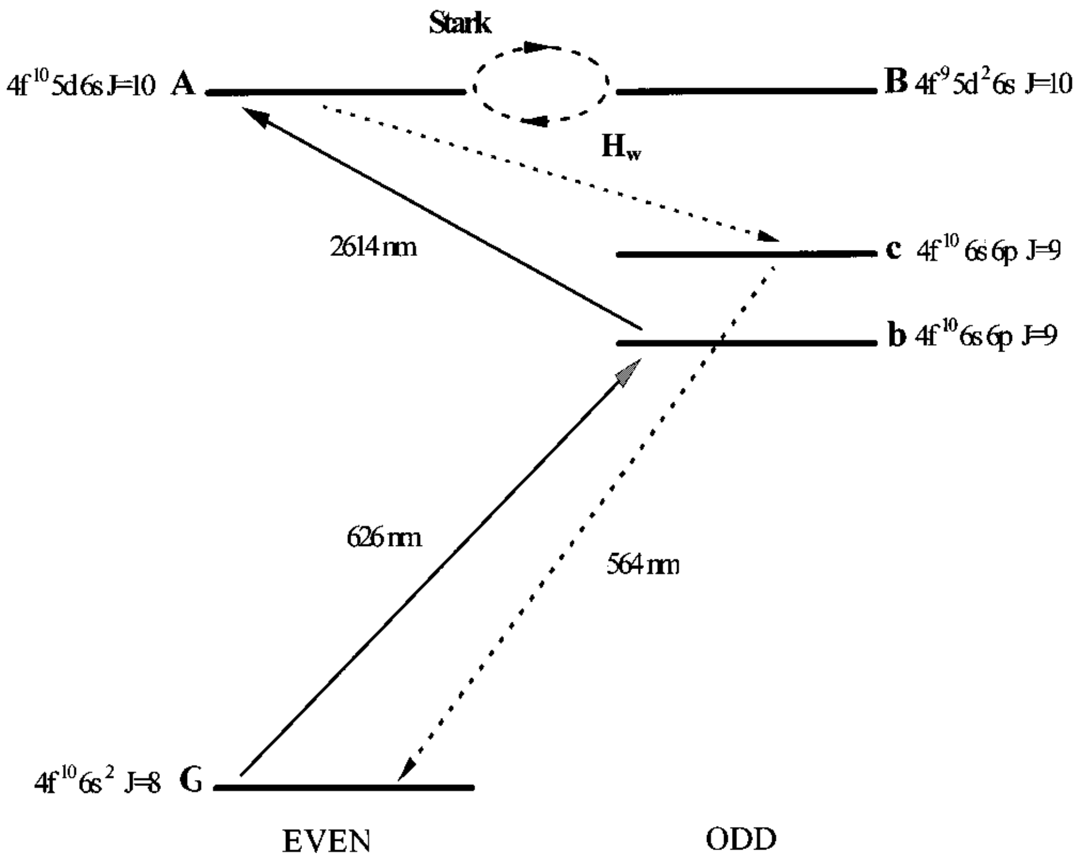

**Reversals**

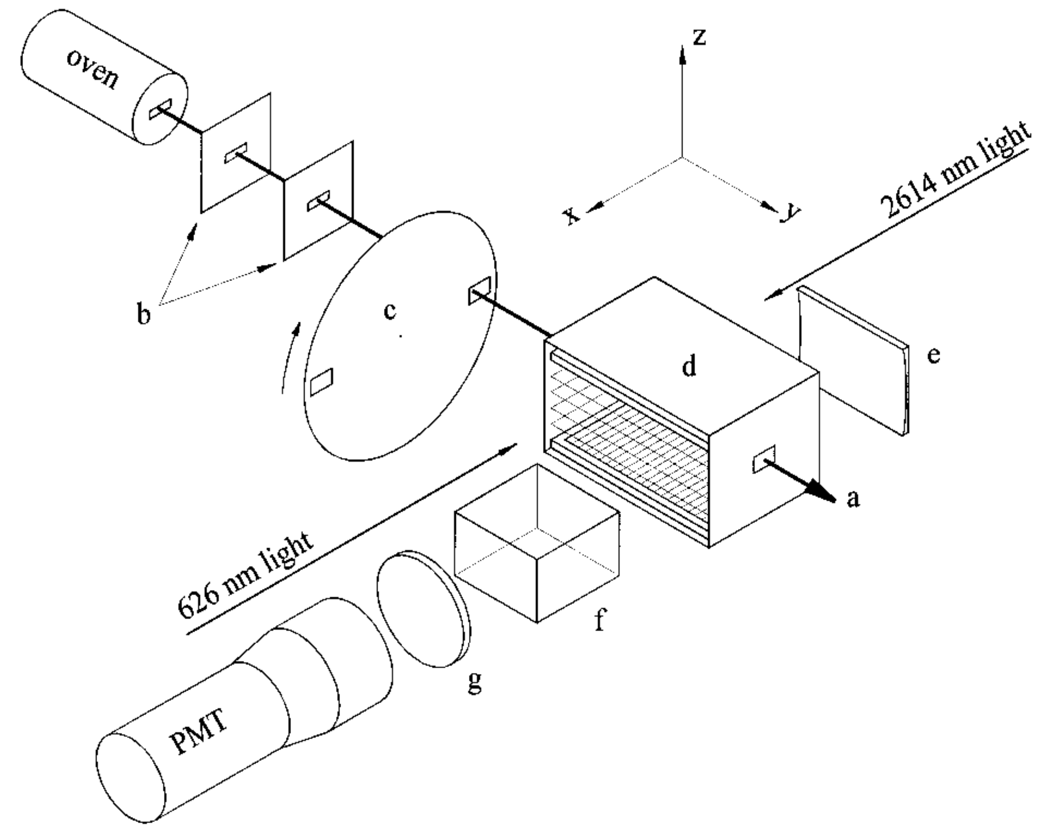
- Detuning
- Magnetic field
- Electric field

⇒ **PNC asymmetry**

# APV in $^{163}$Dy

Past




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]

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# Moving forward...

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*

D. Budker†
*Department of Physics, University of California at Berkeley, Berkeley, California 94720-7300, USA 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)

# Moving forward...

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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*

[2]*Physics Division, Los Alamos National Laboratory, P-23, MS-H803, Los Alamos, New Mexico 87545, USA*

[3]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

(Received 1 September 2006; published 26 January 2007)

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

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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,‡]



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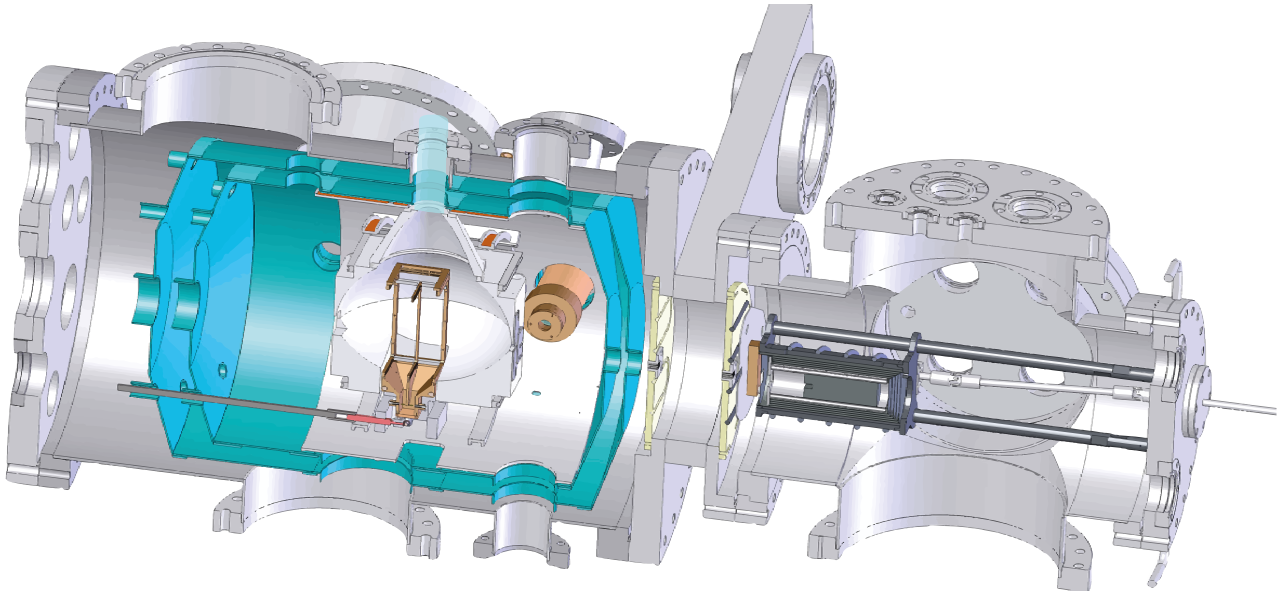
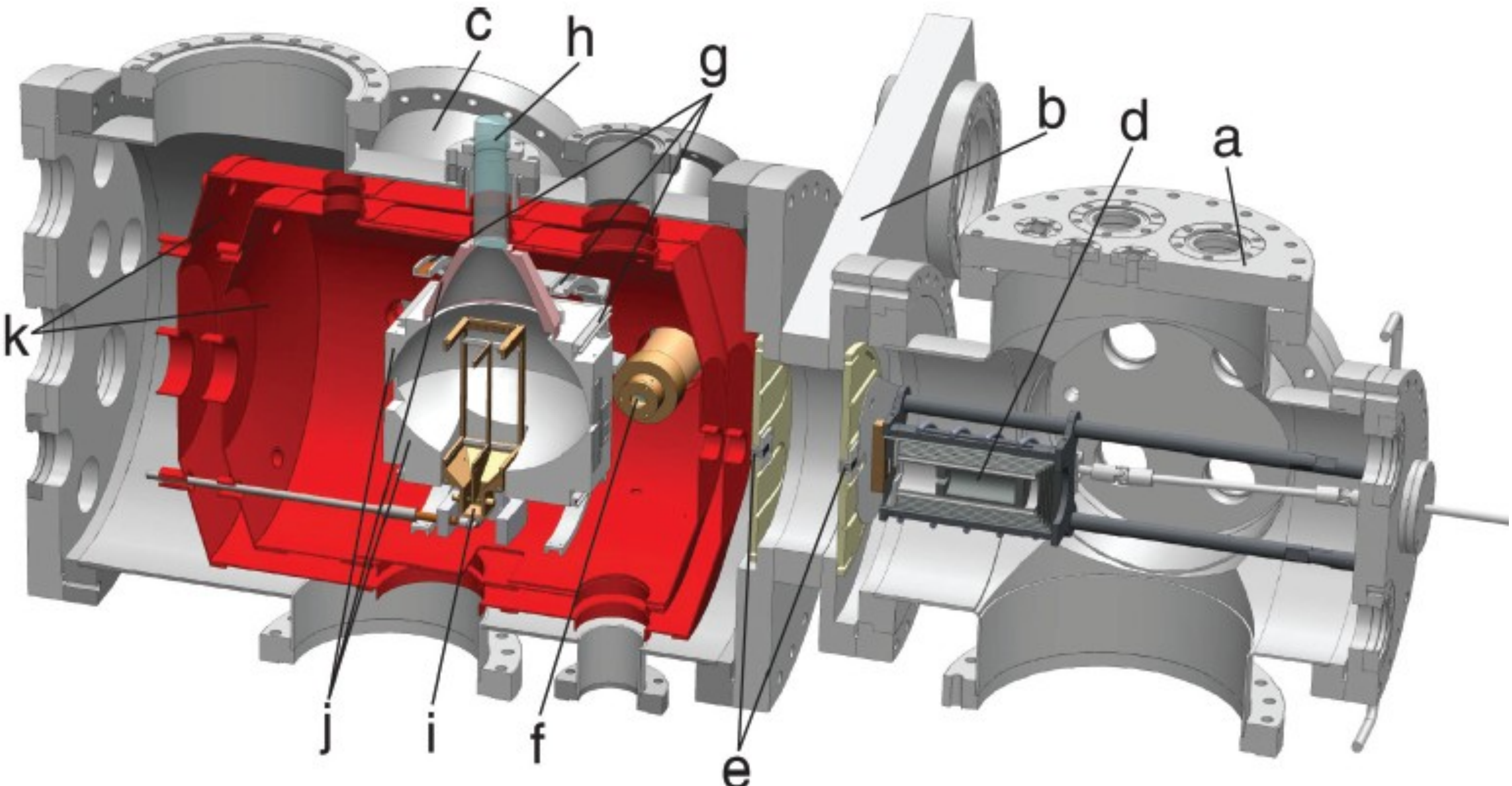
# Present

## New apparatus



# Present

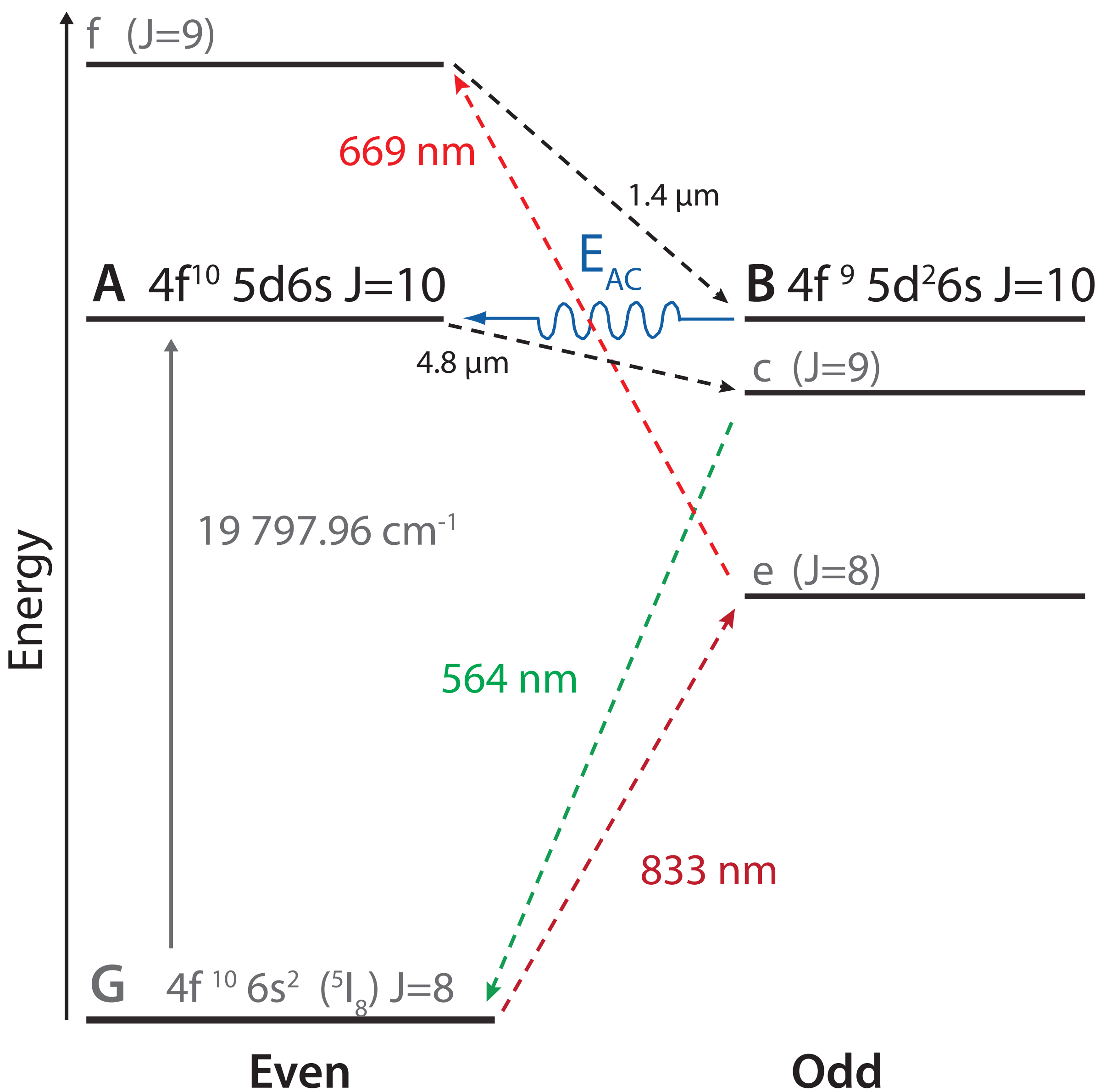


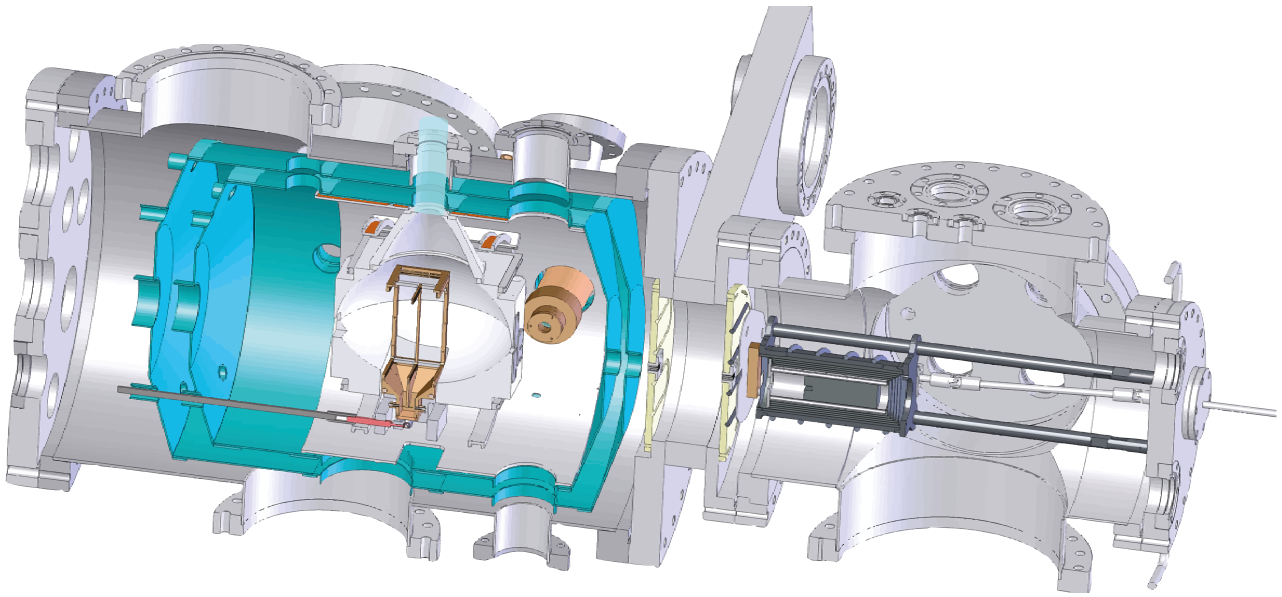

a) oven chamber
b) gate valve
c) interaction-region chamber
d) Dy oven
e) vacuum chokes
f) laser access/in-vacuum polarizer

g) magnetic-field coils
h) light pipe
i) rf electrodes
j) light-collection mirrors
k) two-layer magnetic shielding

# Present

| CW lasers & New transition scheme | New apparatus |
|---|---|



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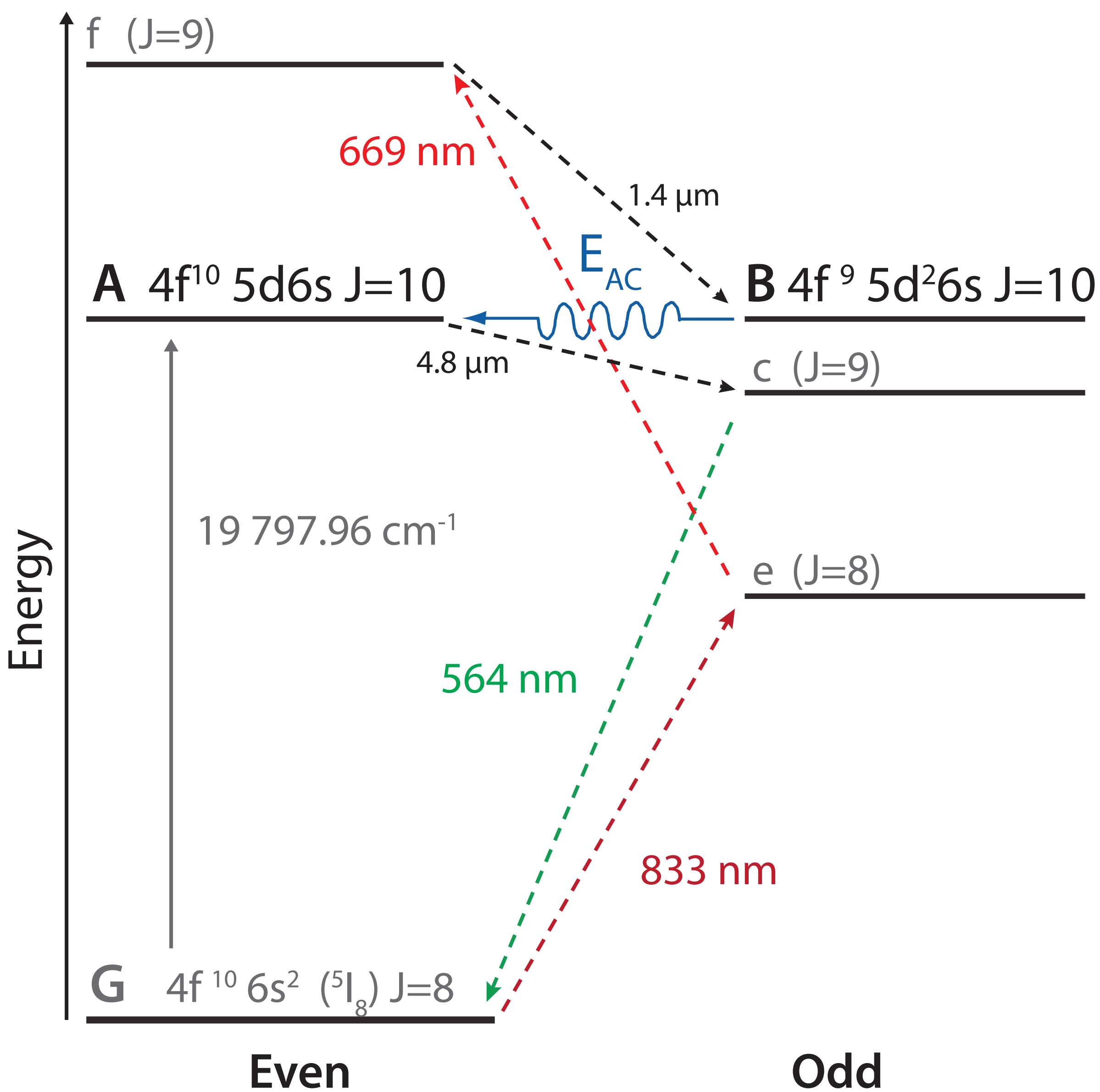


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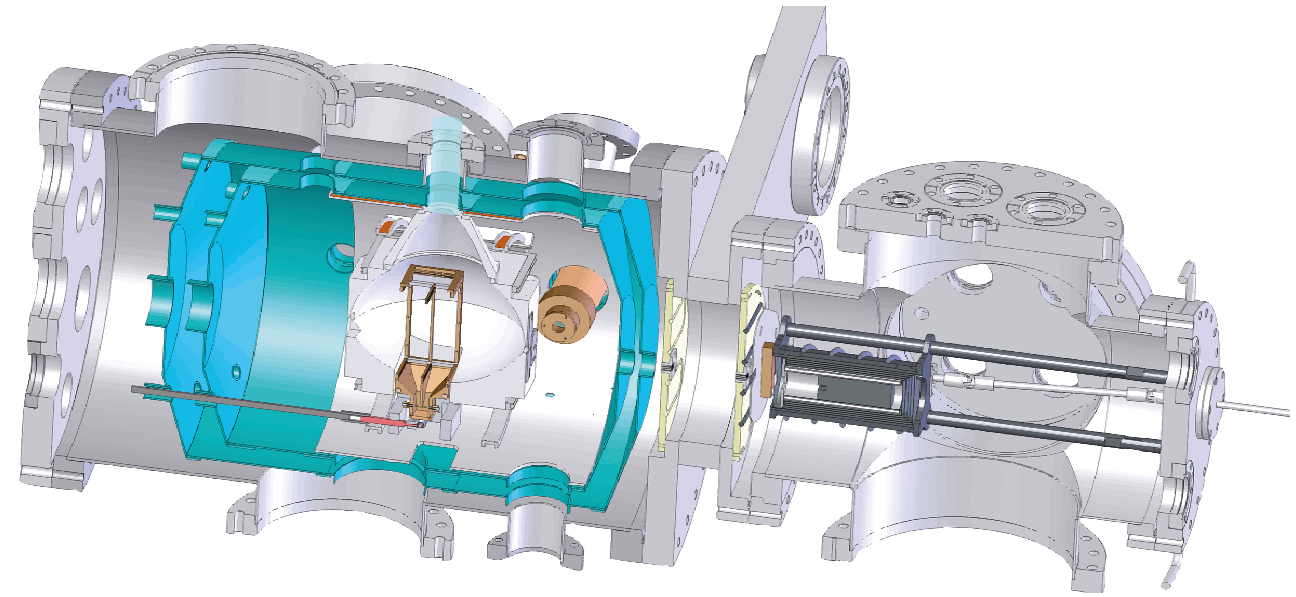


## Status

**RF-spectroscopy : 200mHz in 10 minutes**

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

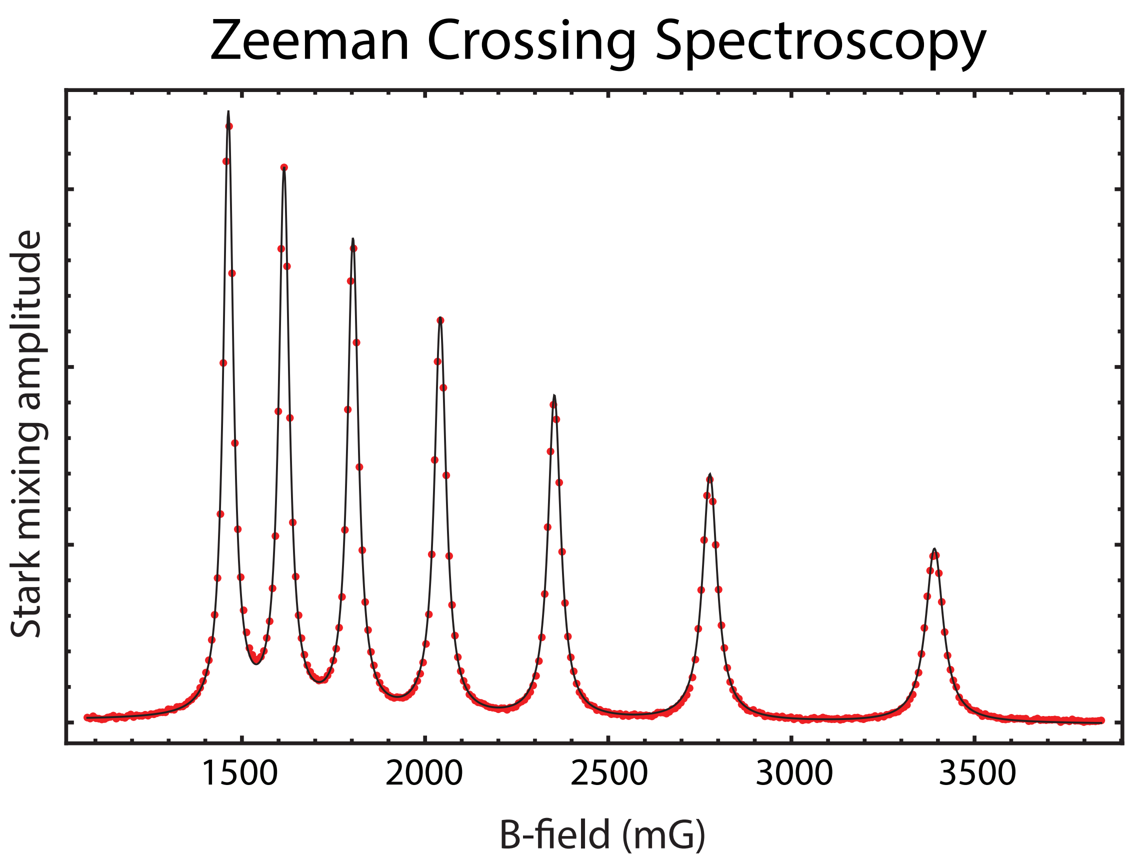
**New Limits on Variation of the Fine-Structure Constant Using Atomic Dysprosium**

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**

# APV in $^{163}$Dy

# Started taking APV data again!




**Improved theory (2010)**

$|H_W| = 4 \pm 4$ Hz

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

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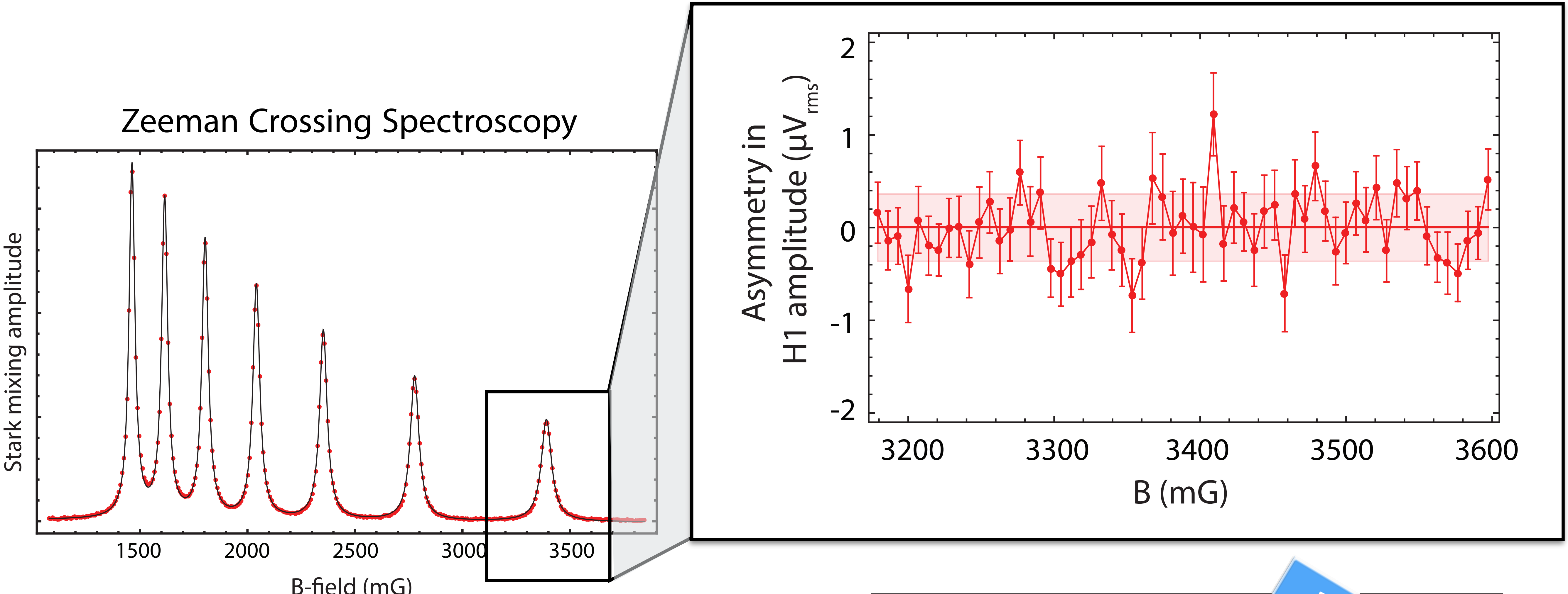


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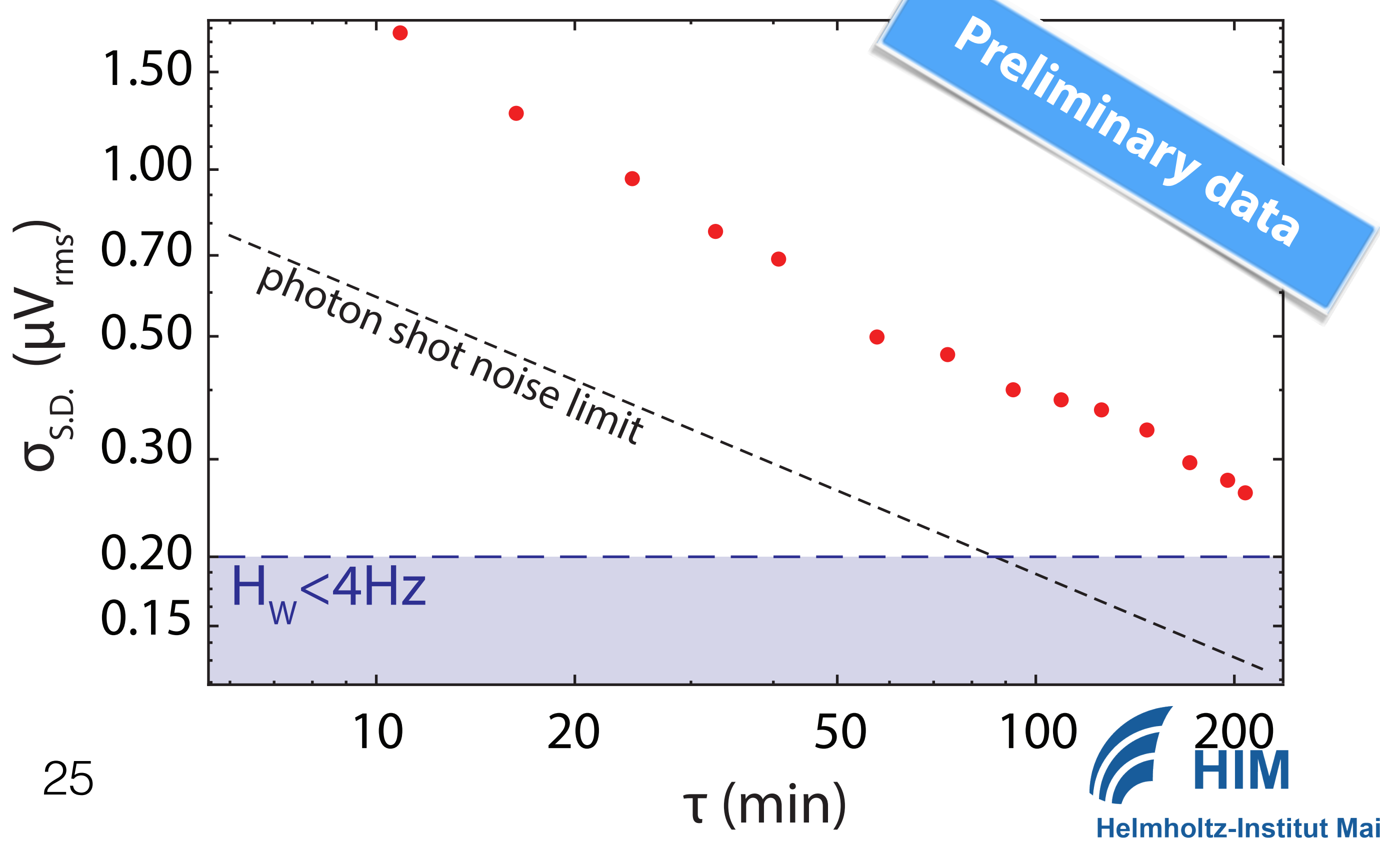




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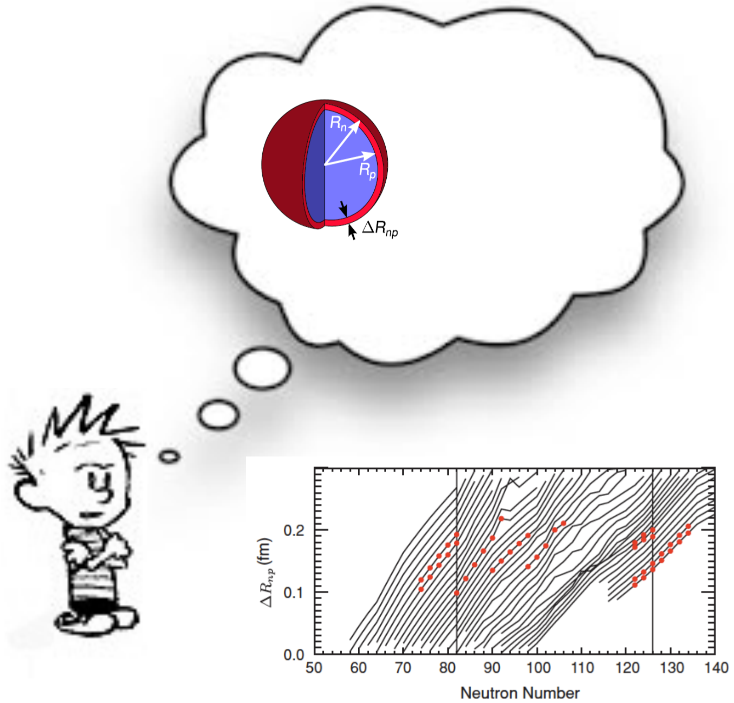
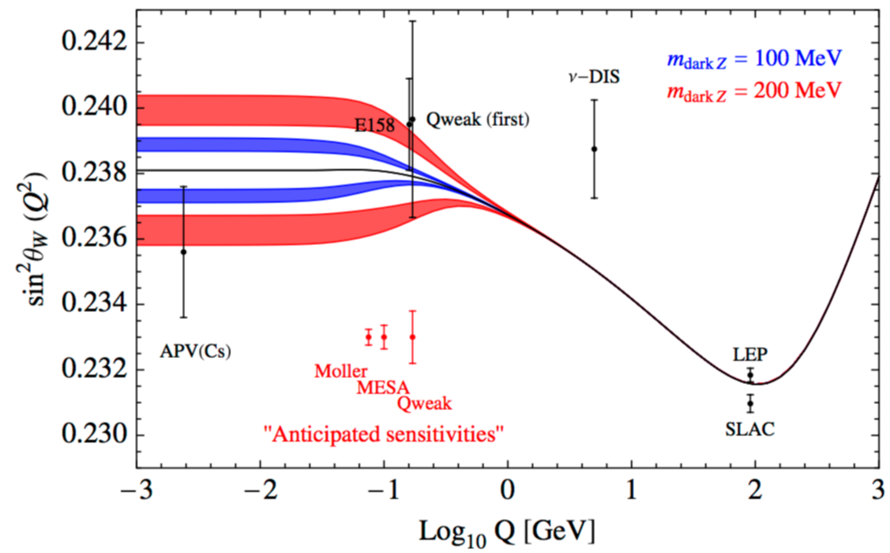
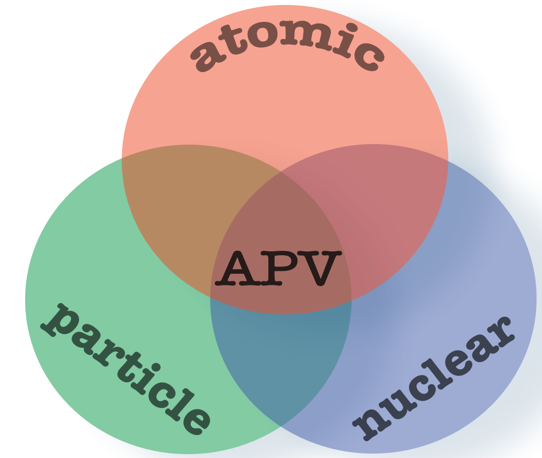
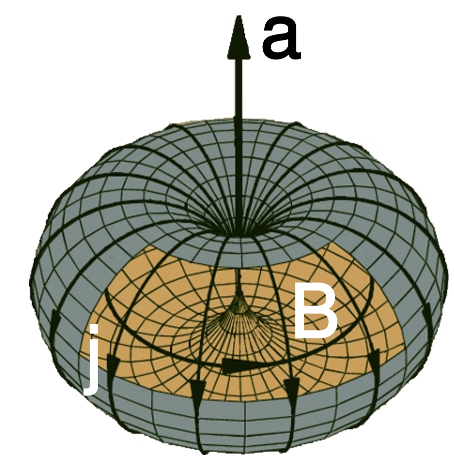
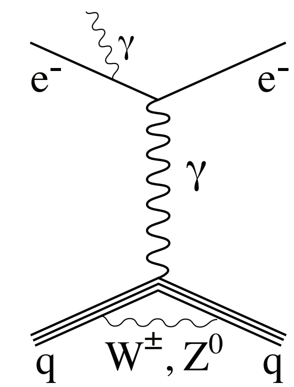


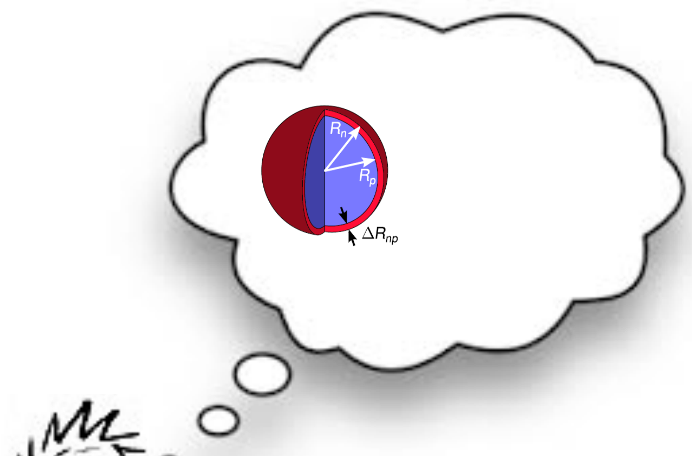



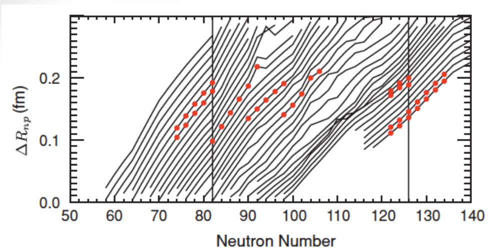



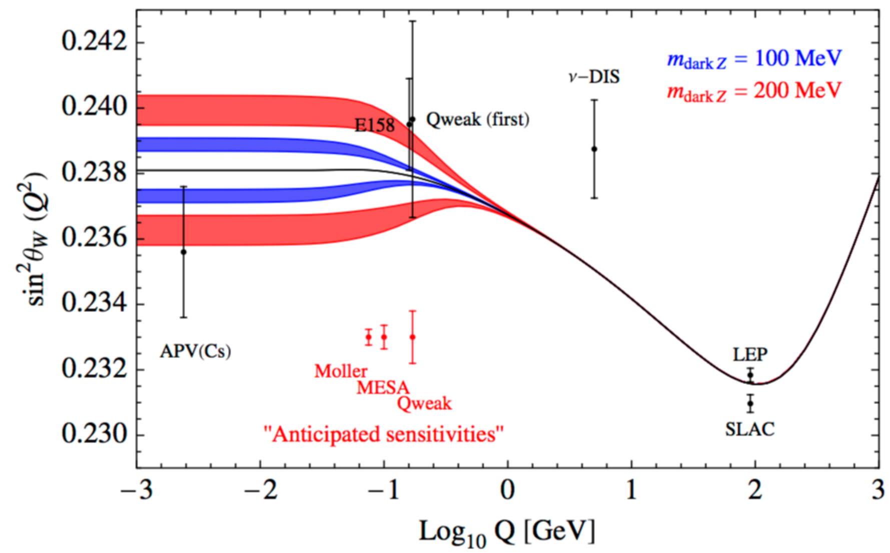



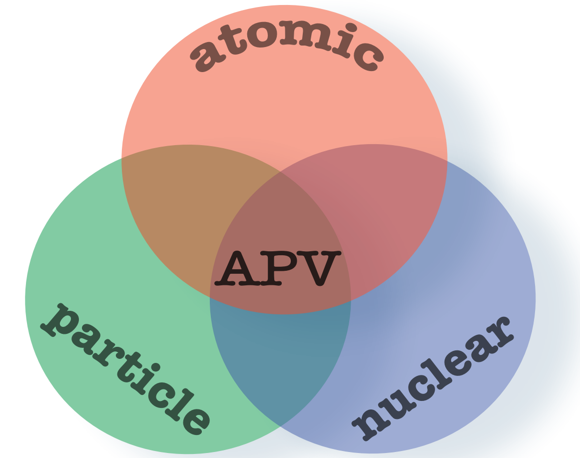
Anapole moment

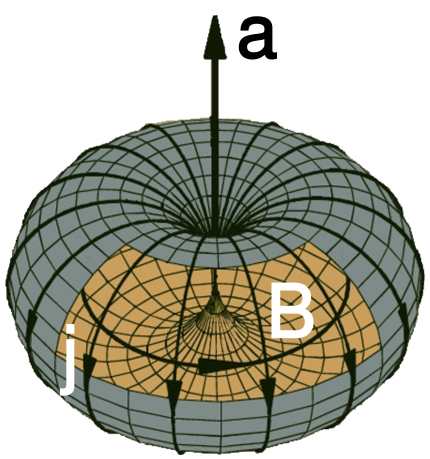
# Future

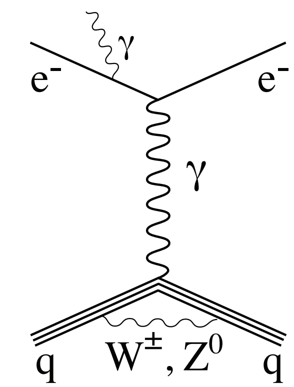


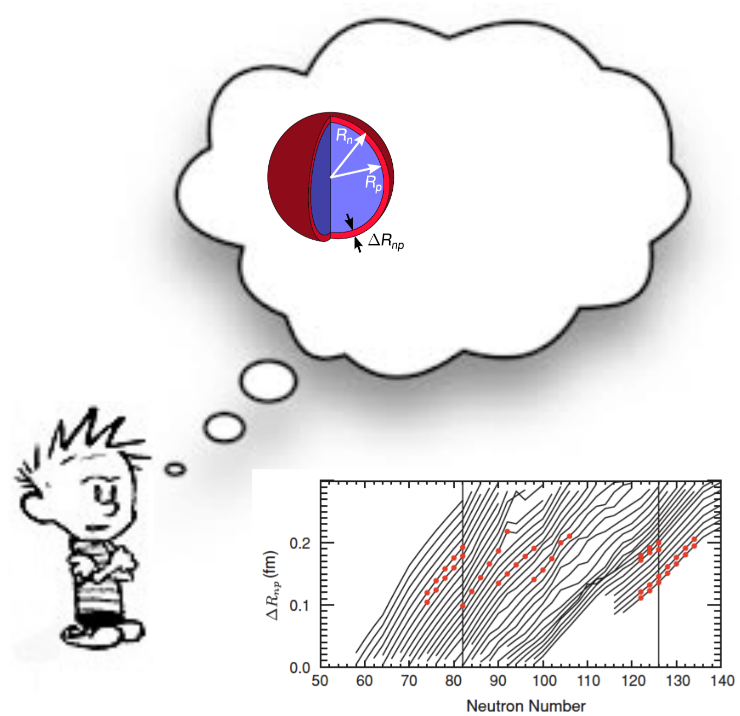



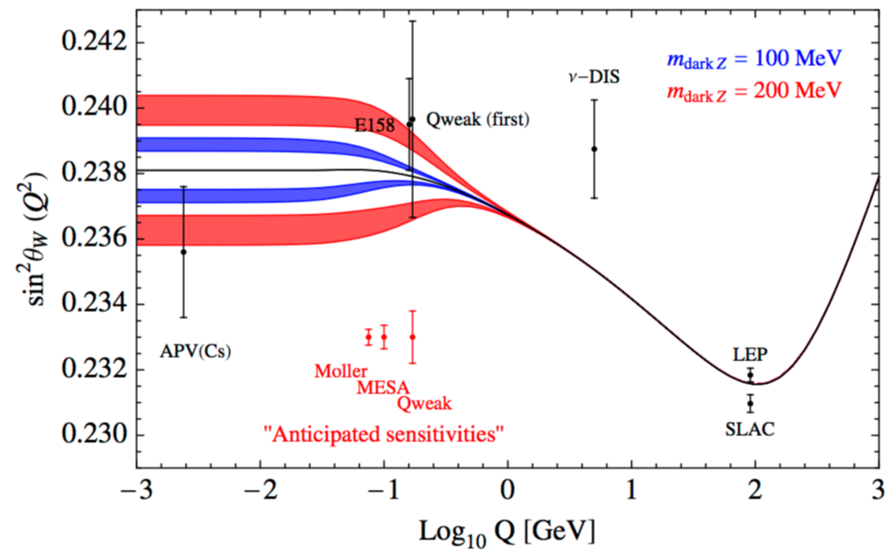



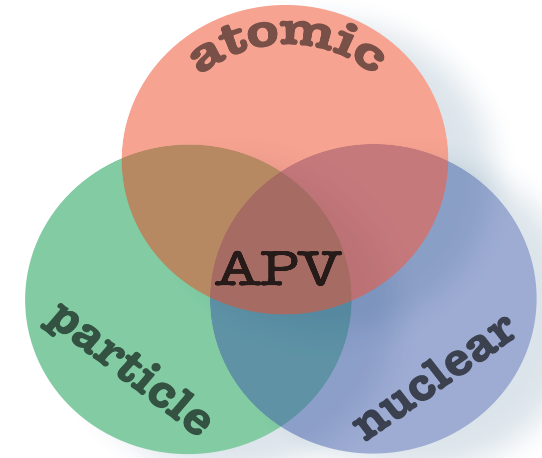

Anapole moment

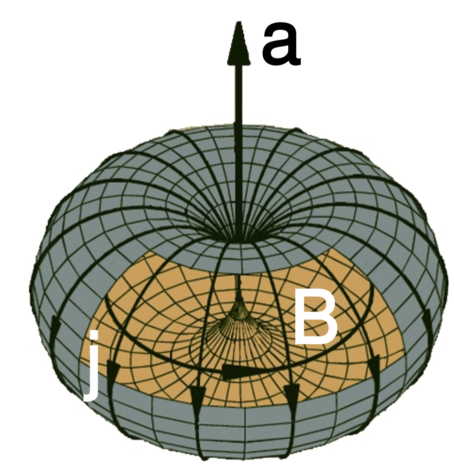
# Future

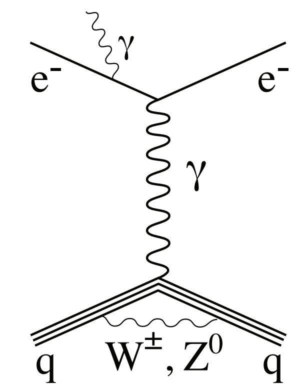
- Bring experiment in Mainz 🇺🇸 ➡ 🇩🇪



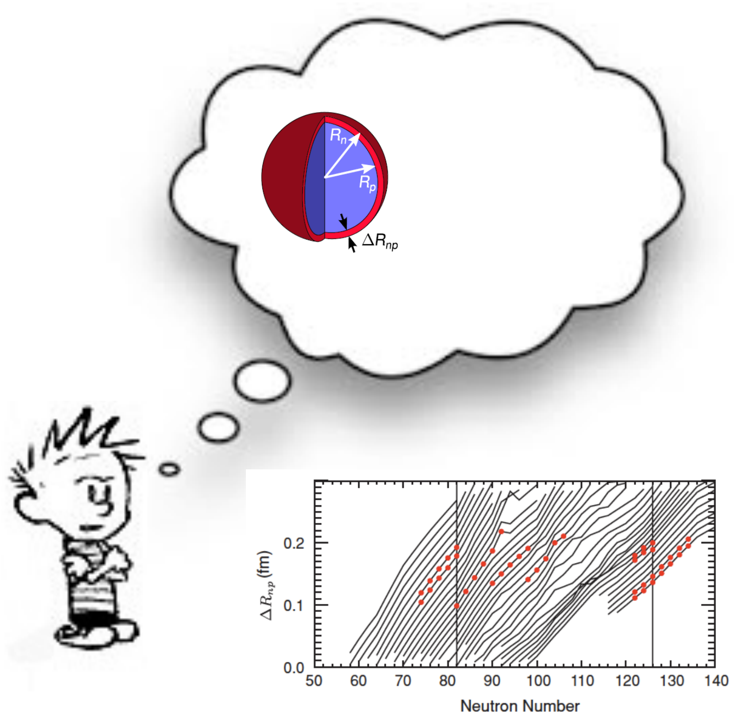



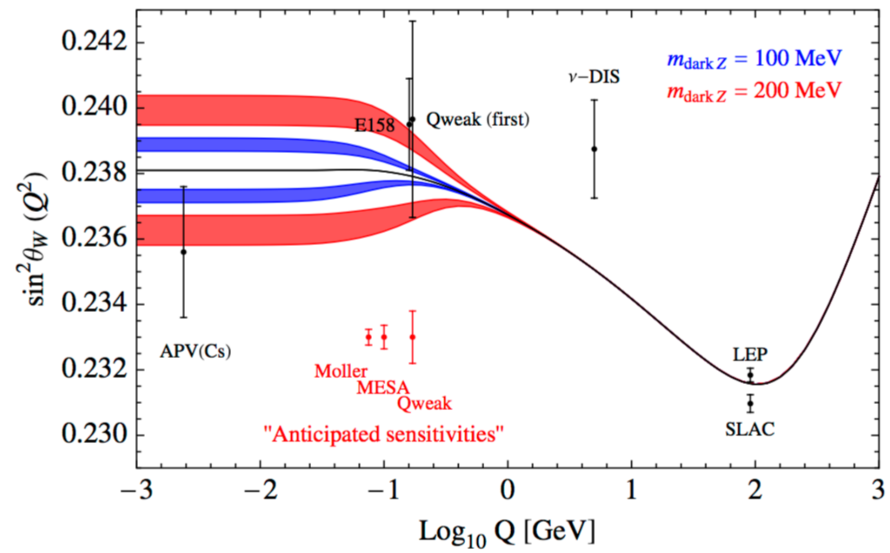



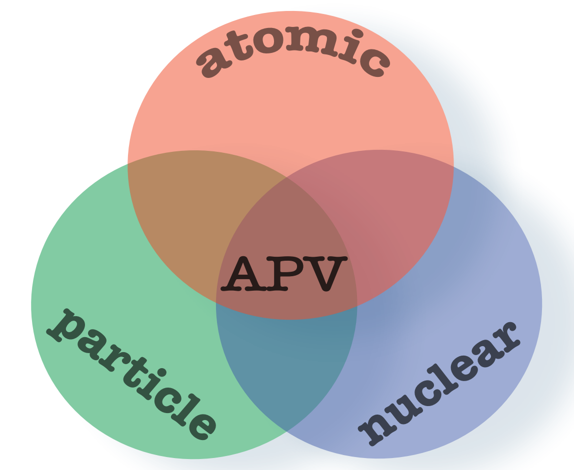

Anapole moment

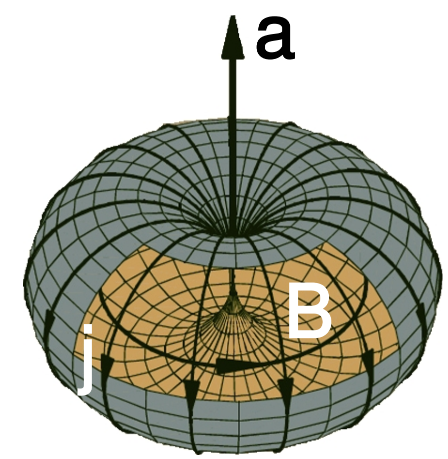
# Future

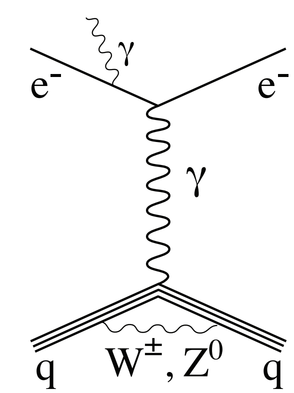
- Bring experiment in Mainz 🇺🇸 ➡ 🇩🇪
- Re-setup experiment + 421 pumping



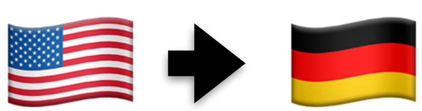



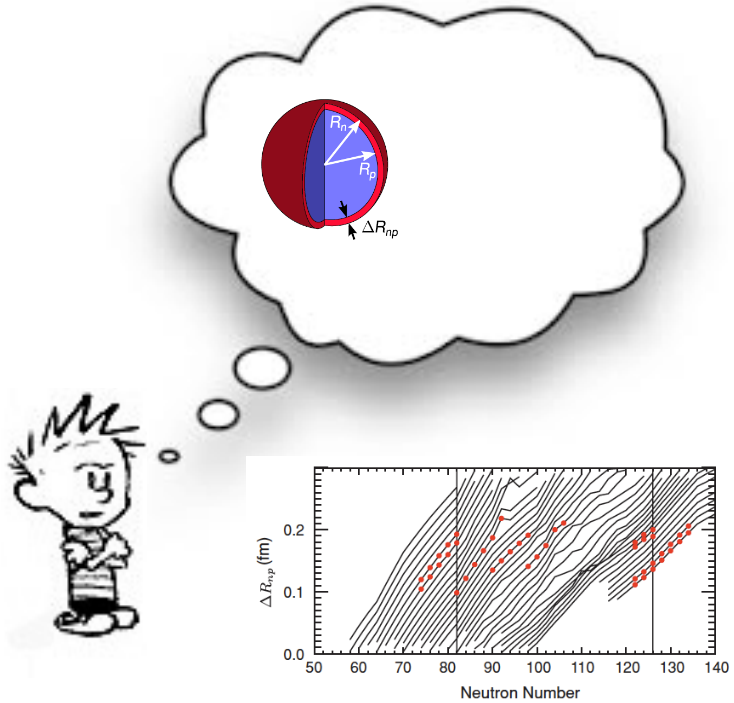



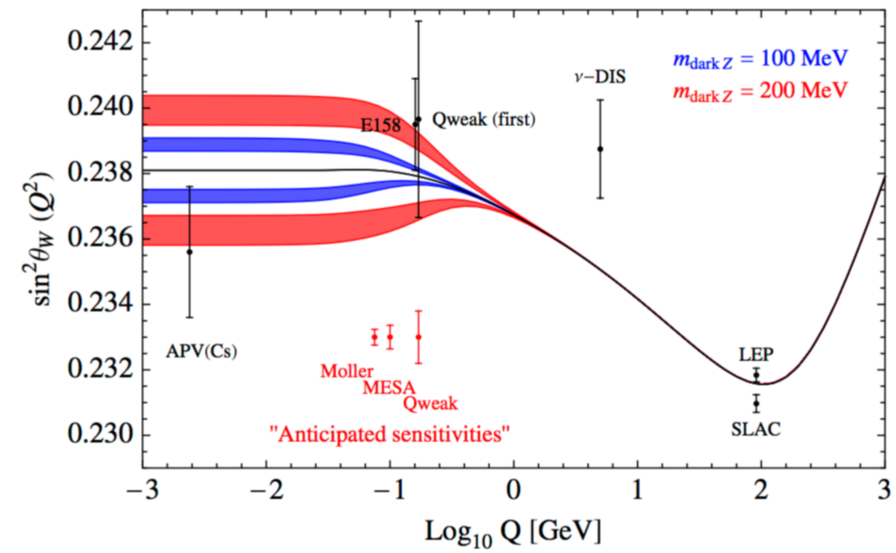



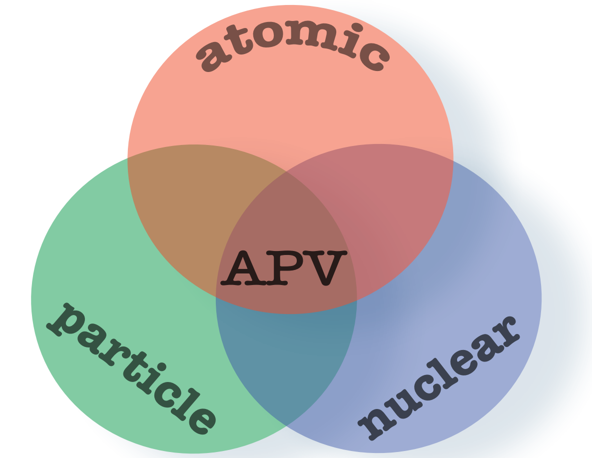
Anapole moment

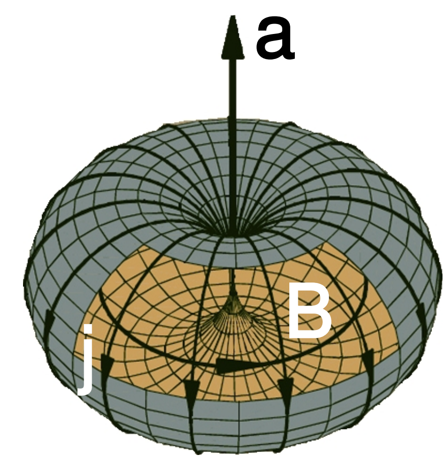
# Future

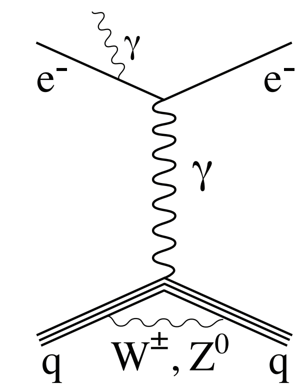
- Bring experiment in Mainz 
- Re-setup experiment + 421 pumping
- First PNC measurement
- PNC in chain of isotopes



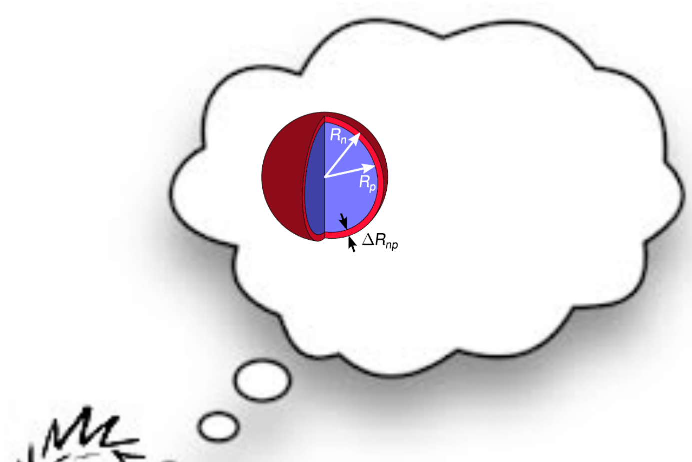



Anapole moment

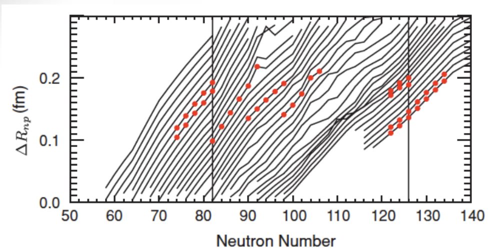
# Future

- Bring experiment in Mainz
- Re-setup experiment + 421 pumping
- First PNC measurement
- PNC in chain of isotopes

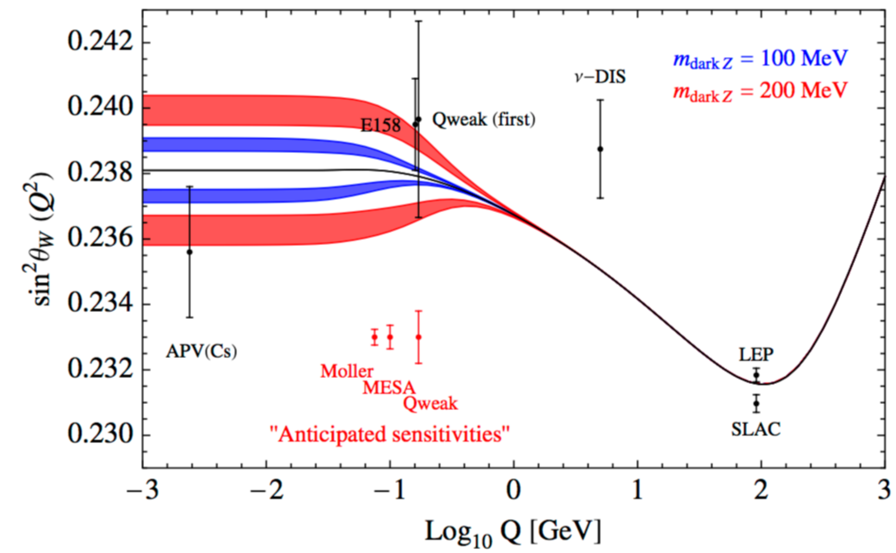
$t_0$



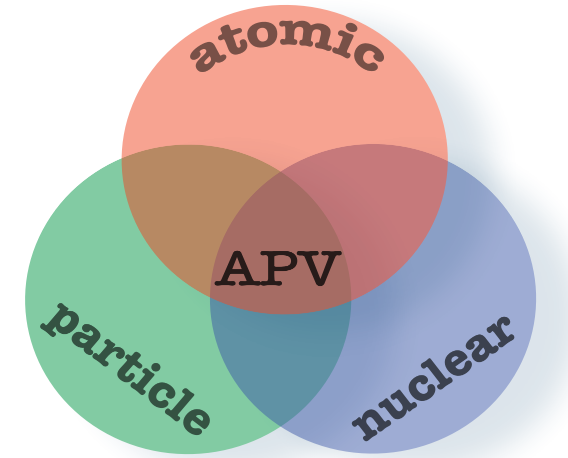




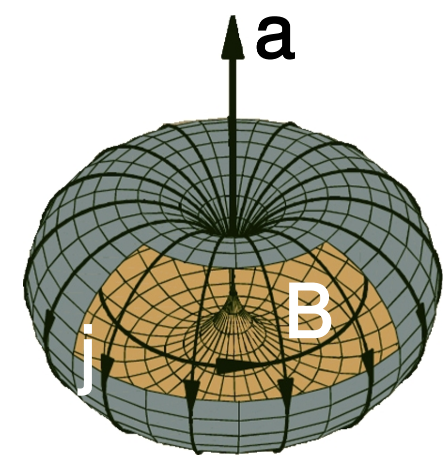




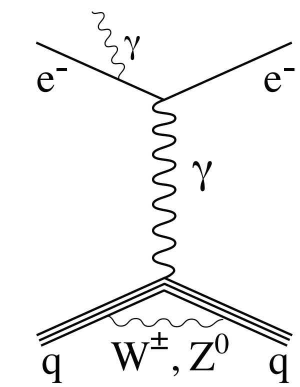














# Future

- Bring experiment in Mainz — $t_0$
- Re-setup experiment + 421 pumping — $t_0$+ 2 months
- First PNC measurement — $t_0$+ 6 months
- PNC in chain of isotopes — $t_0$+ 1 year

# PNC experiments

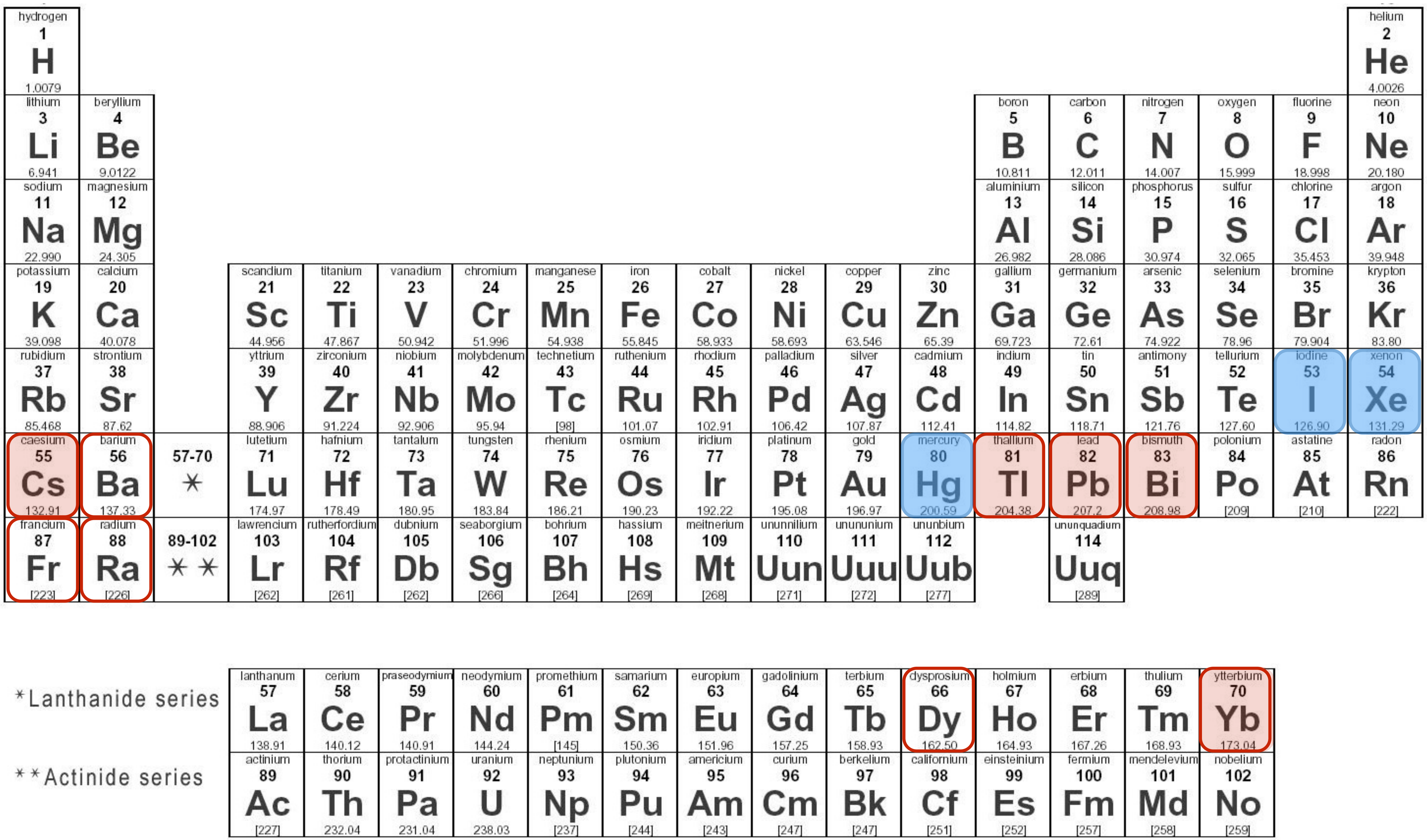
| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| hydrogen 1 H 1.0079 | | | | | | | | | | | | | | | | | | helium 2 He 4.0026 |
| lithium 3 Li 6.941 | beryllium 4 Be 9.0122 | | | | | | | | | | | | boron 5 B 10.811 | carbon 6 C 12.011 | nitrogen 7 N 14.007 | oxygen 8 O 15.999 | fluorine 9 F 18.998 | neon 10 Ne 20.180 |
| sodium 11 Na 22.990 | magnesium 12 Mg 24.305 | | | | | | | | | | | | aluminium 13 Al 26.982 | silicon 14 Si 28.086 | phosphorus 15 P 30.974 | sulfur 16 S 32.065 | chlorine 17 Cl 35.453 | argon 18 Ar 39.948 |
| potassium 19 K 39.098 | calcium 20 Ca 40.078 | | scandium 21 Sc 44.956 | titanium 22 Ti 47.867 | vanadium 23 V 50.942 | chromium 24 Cr 51.996 | manganese 25 Mn 54.938 | iron 26 Fe 55.845 | cobalt 27 Co 58.933 | nickel 28 Ni 58.693 | copper 29 Cu 63.546 | zinc 30 Zn 65.39 | gallium 31 Ga 69.723 | germanium 32 Ge 72.61 | arsenic 33 As 74.922 | selenium 34 Se 78.96 | bromine 35 Br 79.904 | krypton 36 Kr 83.80 |
| rubidium 37 Rb 85.468 | strontium 38 Sr 87.62 | | yttrium 39 Y 88.906 | zirconium 40 Zr 91.224 | niobium 41 Nb 92.906 | molybdenum 42 Mo 95.94 | technetium 43 Tc [98] | ruthenium 44 Ru 101.07 | rhodium 45 Rh 102.91 | palladium 46 Pd 106.42 | silver 47 Ag 107.87 | cadmium 48 Cd 112.41 | indium 49 In 114.82 | tin 50 Sn 118.71 | antimony 51 Sb 121.76 | tellurium 52 Te 127.60 | iodine 53 I 126.90 | xenon 54 Xe 131.29 |
| caesium 55 Cs 132.91 | barium 56 Ba 137.33 | 57-70 * | lutetium 71 Lu 174.97 | hafnium 72 Hf 178.49 | tantalum 73 Ta 180.95 | tungsten 74 W 183.84 | rhenium 75 Re 186.21 | osmium 76 Os 190.23 | iridium 77 Ir 192.22 | platinum 78 Pt 195.08 | gold 79 Au 196.97 | mercury 80 Hg 200.59 | thallium 81 Tl 204.38 | lead 82 Pb 207.2 | bismuth 83 Bi 208.98 | polonium 84 Po [209] | astatine 85 At [210] | radon 86 Rn [222] |
| francium 87 Fr [223] | radium 88 Ra [226] | 89-102 * * | lawrencium 103 Lr [262] | rutherfordium 104 Rf [261] | dubnium 105 Db [262] | seaborgium 106 Sg [266] | bohrium 107 Bh [264] | hassium 108 Hs [269] | meitnerium 109 Mt [268] | ununnilium 110 Uun [271] | unununium 111 Uuu [272] | ununbium 112 Uub [277] | | ununquadium 114 Uuq [289] | | | | |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| * Lanthanide series | lanthanum 57 La 138.91 | cerium 58 Ce 140.12 | praseodymium 59 Pr 140.91 | neodymium 60 Nd 144.24 | promethium 61 Pm [145] | samarium 62 Sm 150.36 | europium 63 Eu 151.96 | gadolinium 64 Gd 157.25 | terbium 65 Tb 158.93 | dysprosium 66 Dy 162.50 | holmium 67 Ho 164.93 | erbium 68 Er 167.26 | thulium 69 Tm 168.93 | ytterbium 70 Yb 173.04 |
| * * Actinide series | actinium 89 Ac [227] | thorium 90 Th 232.04 | protactinium 91 Pa 231.04 | uranium 92 U 238.03 | neptunium 93 Np [237] | plutonium 94 Pu [244] | americium 95 Am [243] | curium 96 Cm [247] | berkelium 97 Bk [247] | californium 98 Cf [251] | einsteinium 99 Es [252] | fermium 100 Fm [257] | mendelevium 101 Md [258] | nobelium 102 No [259] |

Successful PNC experiments

Ongoing PNC experiments

# PNC experiments




Successful PNC experiments

New **PNC optical-rotation** ideas

Ongoing PNC experiments



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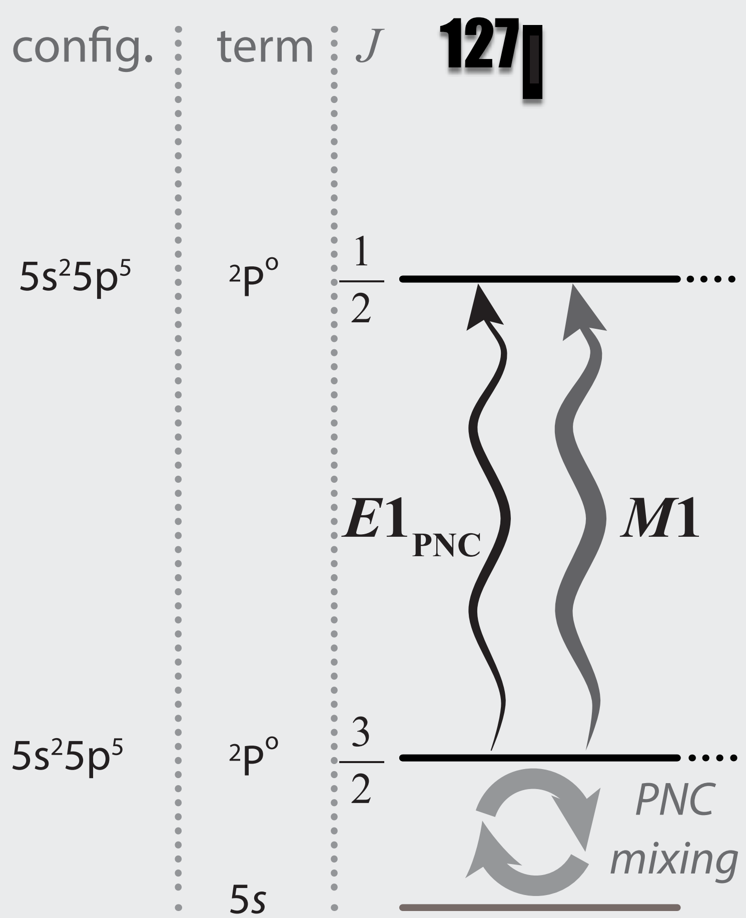
# APV in $^{127}$I

## Transition @ 1315nm



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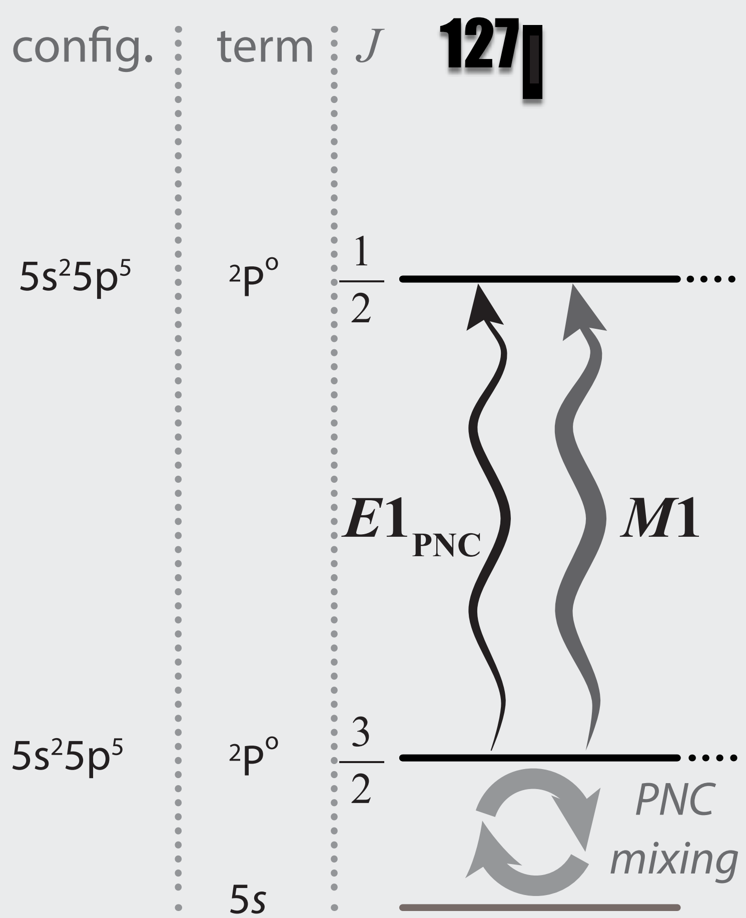
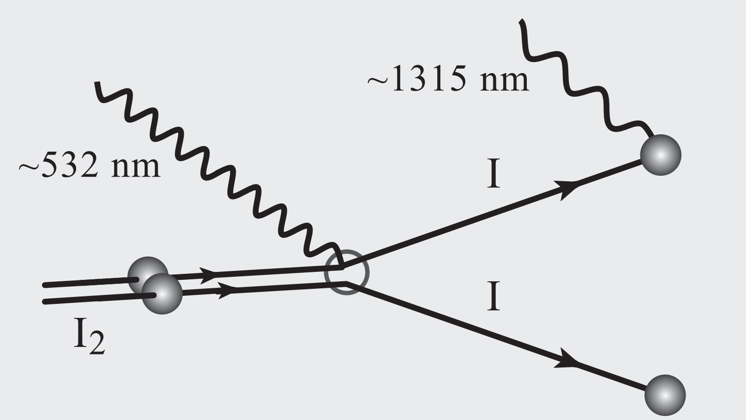
# APV in $^{127}$I

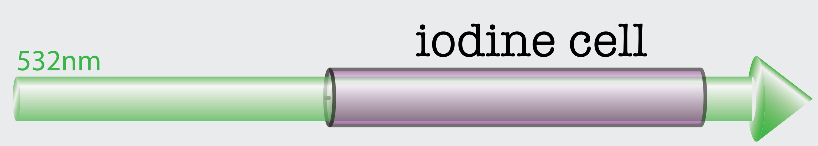
## Transition @ 1315nm



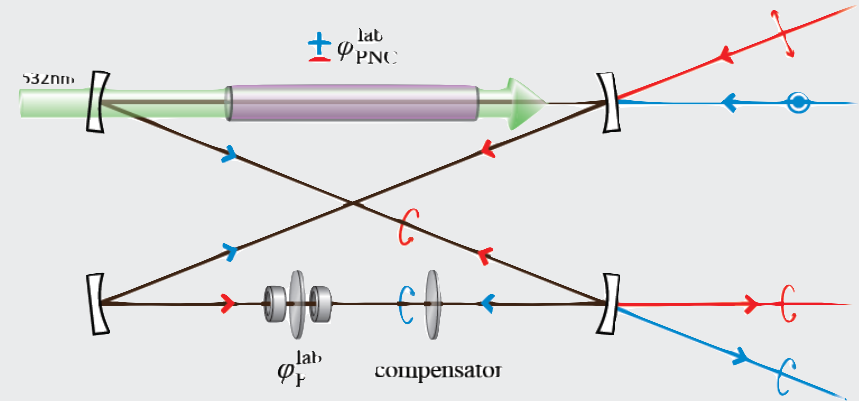

## Iodine

High, steady-state, densities of atomic I from $I_2$ photodissociation




## Cavity-enhanced PNC-OR




- Pathlength enhancements N~$10^4$
- **2 Signal reversals**
- Background subtraction
- Room temperature

Novel technique that allowed us to think of new systems!



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# APV in $^{127}$I

RAPID COMMUNICATIONS

PHYSICAL REVIEW A 87, 040101(R) (2013)

**Calculation of parity-nonconserving optical rotation in iodine at 1315 nm**

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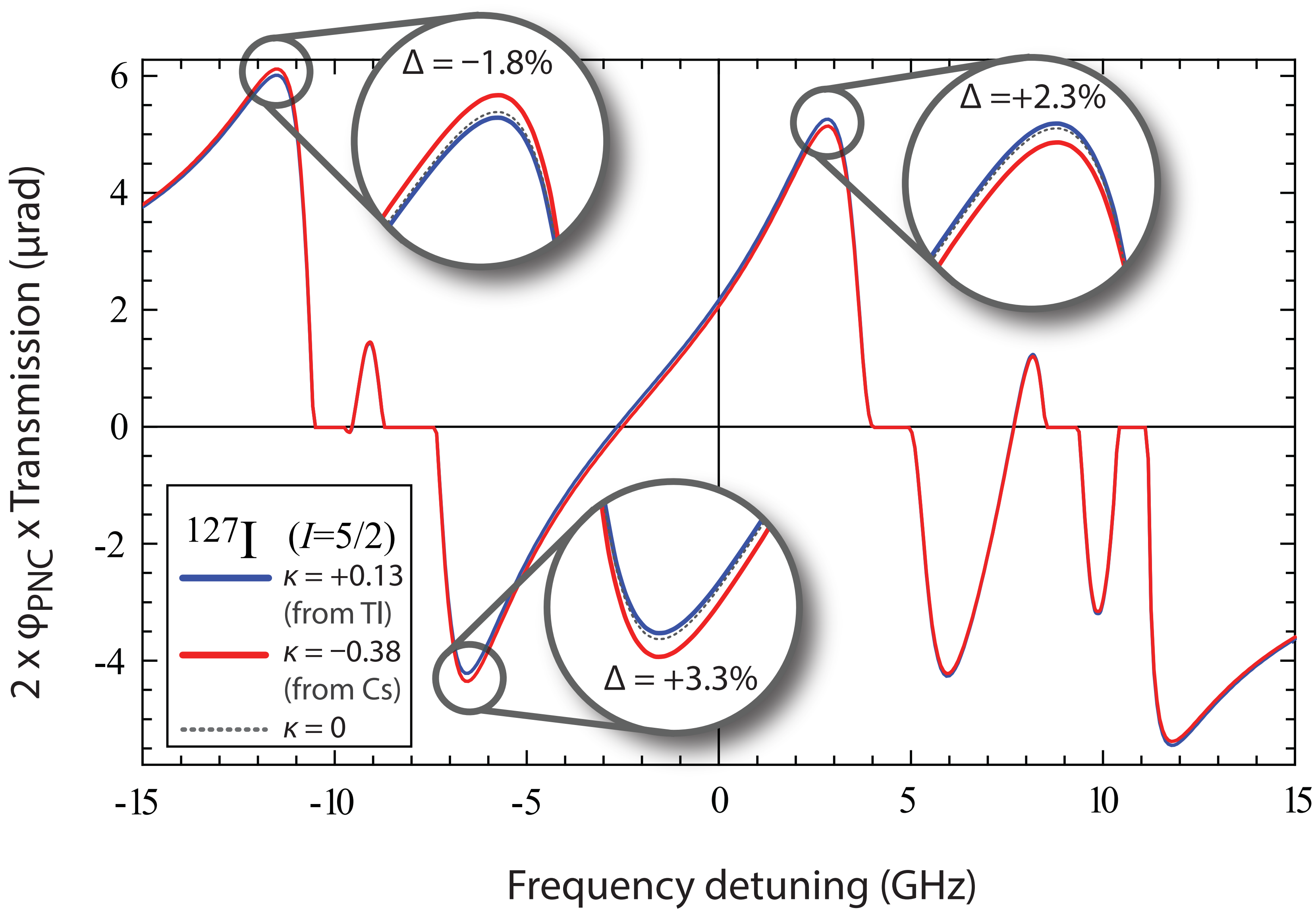
(Received 25 January 2013; published 1 April 2013)




## Predictions & updates:

- ☐ Large predicted signals (2-30x Tl)
- ☐ Potential to resolve disagreement between Cs and Tl NSD-PNC measurements

- ☑ 2 Fast **signal reversals**
- ☑ Fast background subtraction
- ☑ Room temperature

Evanescent-wave and ambient chiral sensing by signal-reversing cavity ringdown polarimetry.
Sofikitis et al., Nature 514, 7520 (2014)



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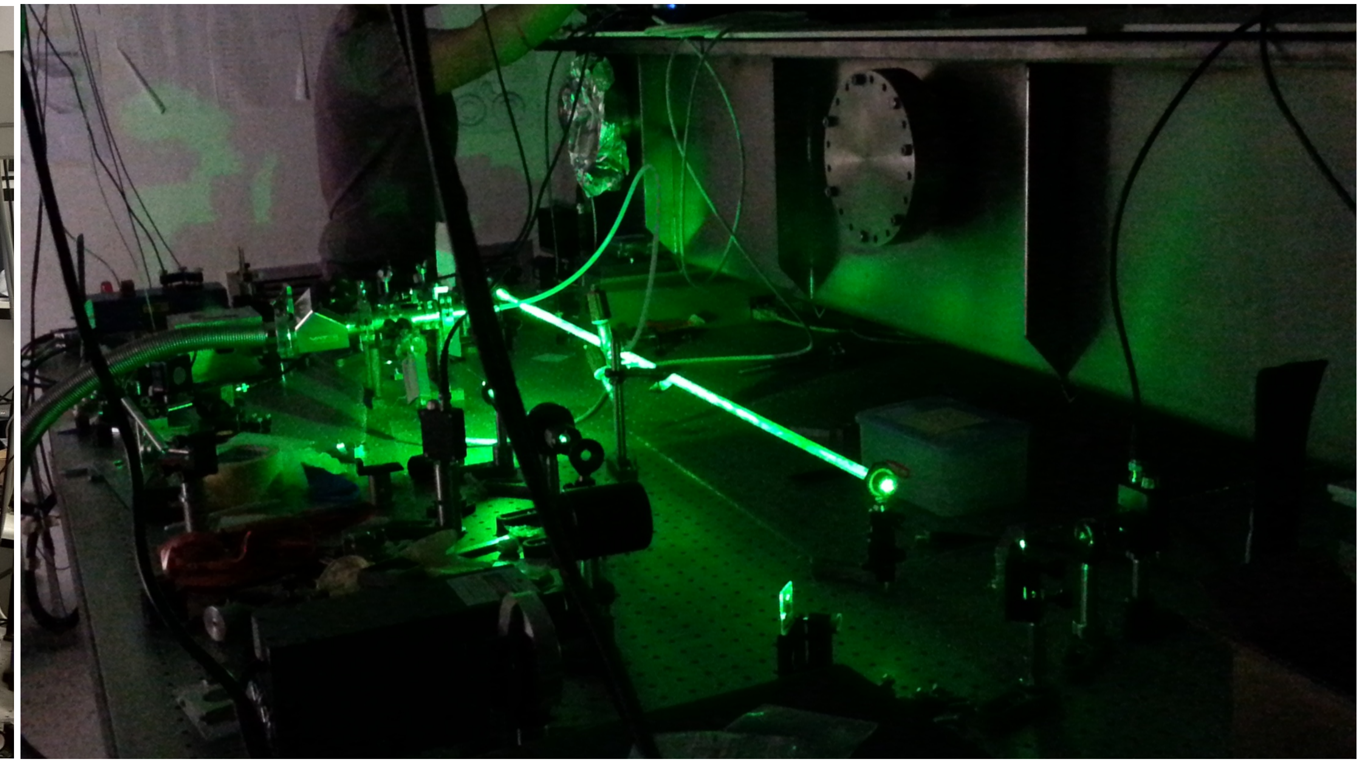
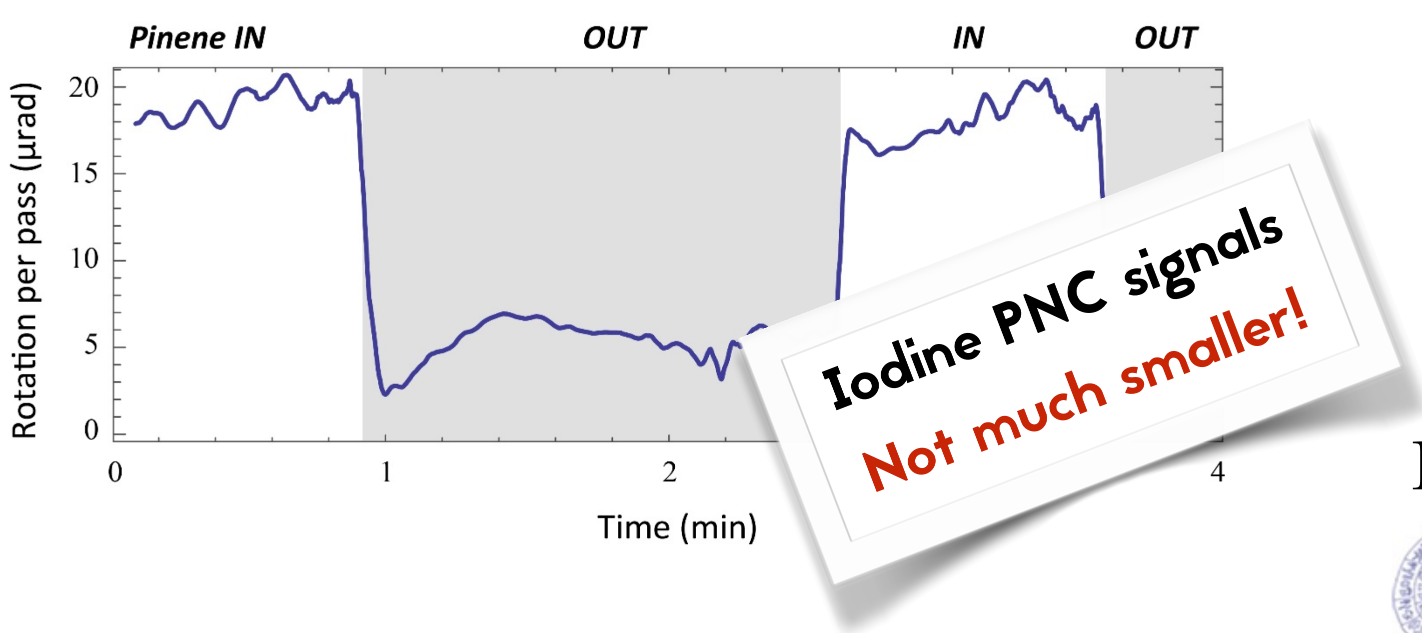
# Towards Iodine-PNC in Crete

## Setup

## Iodine cell



## Proof-of-Principle

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**Thank you!**

+

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