Parity Violation in Diatomic Molecules

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Outline

1. Introduction: Parity violating effects, motivation
2. Why Diatomic Molecules?
3. The Experiment: Schematic, signal
4. Level Crossing Spectroscopy in ^{138}BaF
5. First PV Data with ^{138}BaF: Evidence of systematics
6. E & B Field Systematics: How to measure & eliminate
7. New Data
8. Future Work

Parity Violation

<u>Nuclear Spin Independent (NSI)</u>

Every nucleon contributes

$$H_{\text{NSI}} \propto (\vec{\sigma} \cdot \vec{p})\delta^3(\vec{r})$$

<u>Nuclear Spin Dependent (NSD)</u>

Only unpaired nucleons contribute

$$H_{\text{NSD}} \propto (\vec{\sigma} \cdot \vec{I})(\vec{\sigma} \cdot \vec{p})\delta^3(\vec{r})$$

$\vec{\sigma}$: electron spin

$\vec{p}$: electron mom.

$\vec{I}$: nuclear spin

$\vec{r}$: electron pos.

$\longrightarrow$ NSD PV smaller, more difficult to measure.

Best measurement: Wieman ^{133}Cs

Uncertainties:

NSI 1%

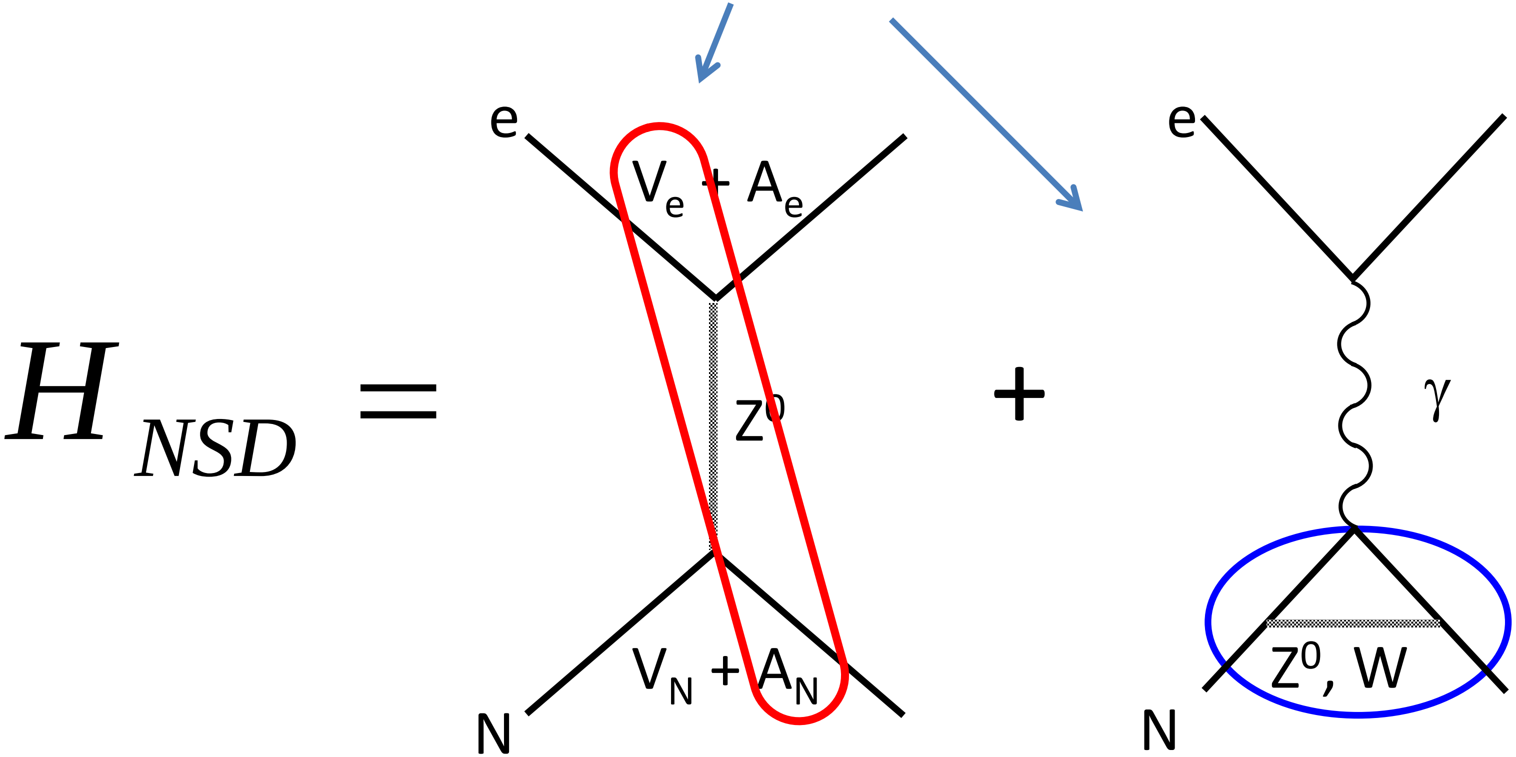
NSD 14%

Also: ^{133}Cs is the <u>only</u> nonzero measurement of NSD in atoms

Using diatomic molecules enhances NSD

NSD PV Effects

$$H_{NSD} \propto (\kappa_Z + \kappa_a)(\vec{\sigma}\cdot\vec{I})(\vec{\sigma}\cdot\vec{p})\,\delta^3(\vec{r})$$



Z^0 exchange

Independent of nuclear mass A

Anapole Moment

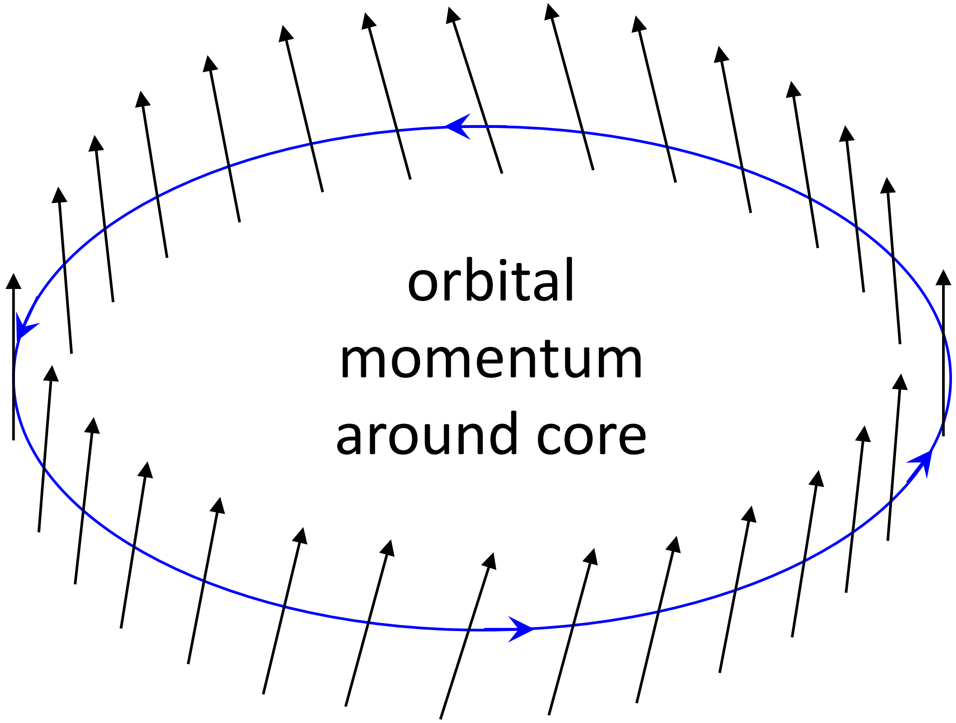
Proportional to $A^{2/3}$

Can differentiate effects by measuring multiple nuclear species

Anapole Moment

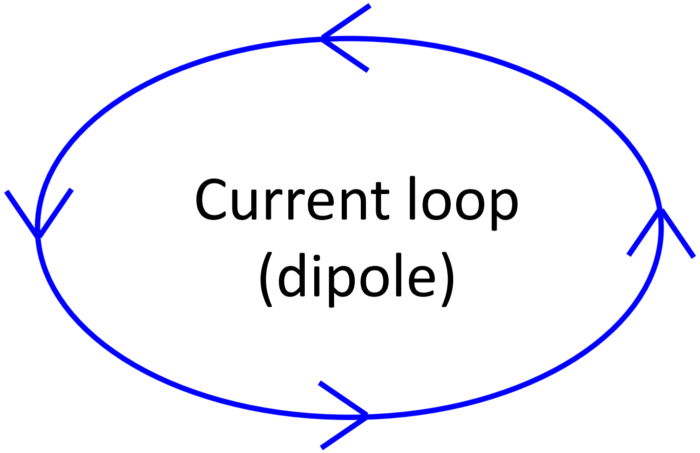
Simple model for nuclear anapole

(valence nucleon + constant-density core):



orbital
momentum
around core

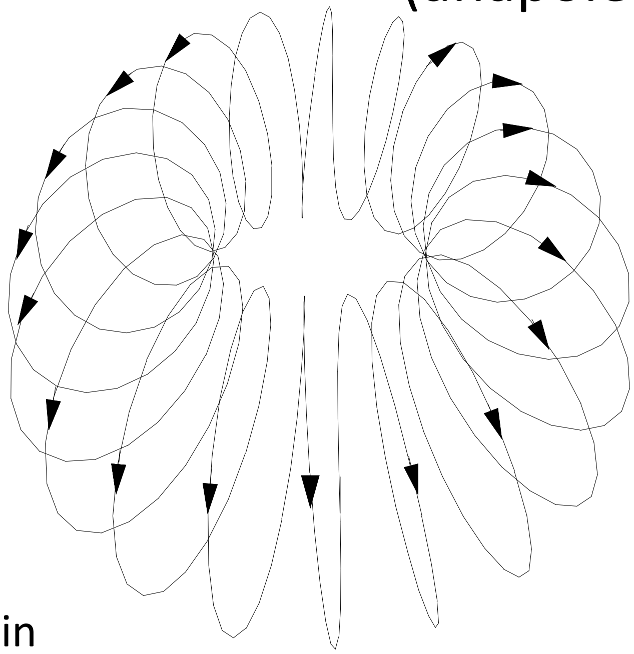
=



Current loop
(dipole)

+

Current helix
(anapole)



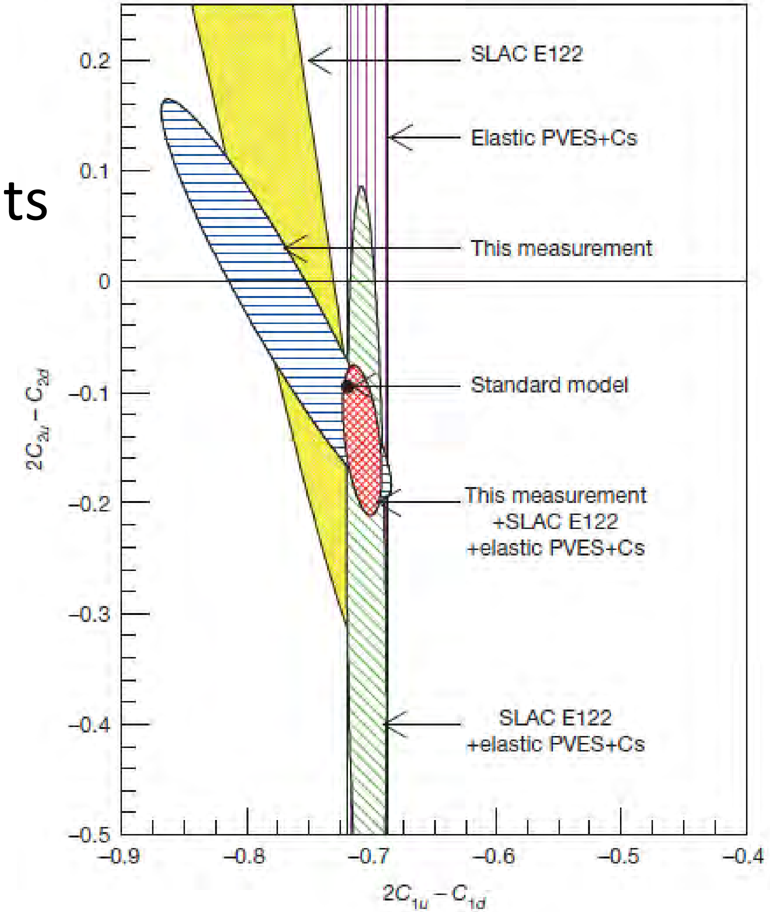
Causes delta
function vector
potential at origin

spin tilted along momentum
due to weak interaction
($\sigma \cdot p$ helicity term)

Motivation

Z^0 Exchange

- Electron – nucleon weak coupling constants (C_{2N}, C_{2P})
- Related to fundamental electron-quark weak coupling constants (C_{2u}, C_{2d})
- Complementary to PVDIS measurements (different linear combinations of C_2 constants)



"Measurement of parity violation in electron-quark scattering"
The Jefferson Lab PVDIS Collaboration
Nature **506**, 67-70

Anapole Moment

- Nucleon – nucleon coupling constants
- Nuclear structure
- "Anapole Moment Table" - unique signatures for each nuclear species

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Even / Odd State Mixing

$$\hat{P}|+\rangle = |+\rangle$$
$$\hat{P}|-\rangle = -|-\rangle$$

Atomic, molecular states are parity eigenstates

$$|+\rangle \quad \rightarrow \quad |+\rangle + \delta|-\rangle$$

Weak interaction mixes even & odd states

$$\delta = \frac{\langle + | H_W | - \rangle}{E_+ - E_-} = \frac{iW}{\Delta} \sim \frac{10\,\mathrm{Hz}}{10^{14}\,\mathrm{Hz}} \sim 10^{-13}$$

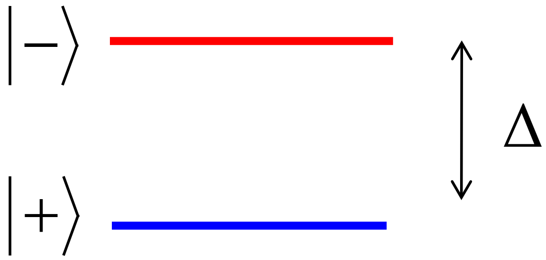
→ δ is very small

1eV

Diatomic Molecules

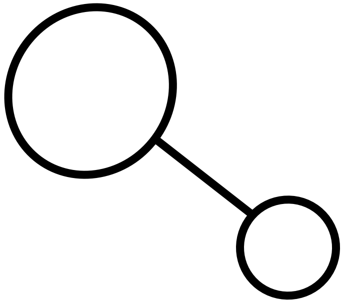
Amplify mixing by making Δ small:

$$\delta = \frac{iW}{\Delta}$$



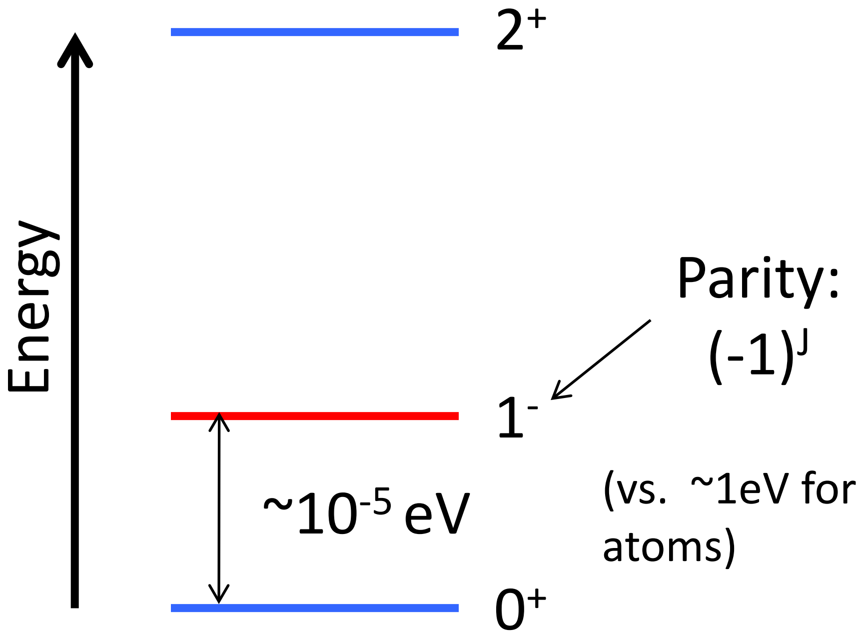
Diatomic molecules:

Large moment of inertia
→ rotational levels have small Δ



$$I \propto MR^2$$

$$E_{rot} = \frac{J^2}{2I}$$



Parity: $(-1)^J$

(vs. ~1eV for atoms)

Zeeman Tuning

Closely spaced levels can be brought to crossing with B-field

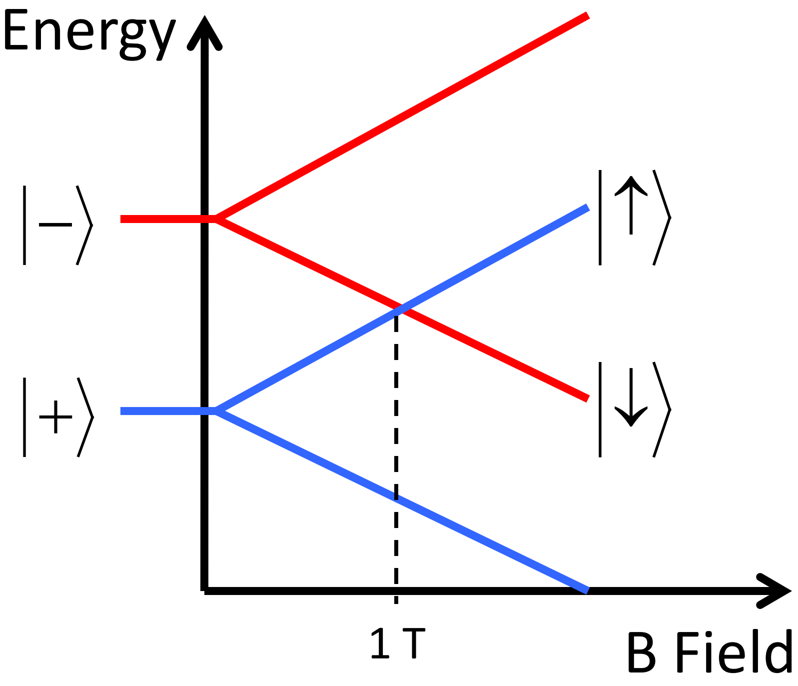
- B-field required: ~ 1 Tesla

$\longrightarrow$ easy with superconducting magnet

- How close?
- 1 part in 10^7 uniformity

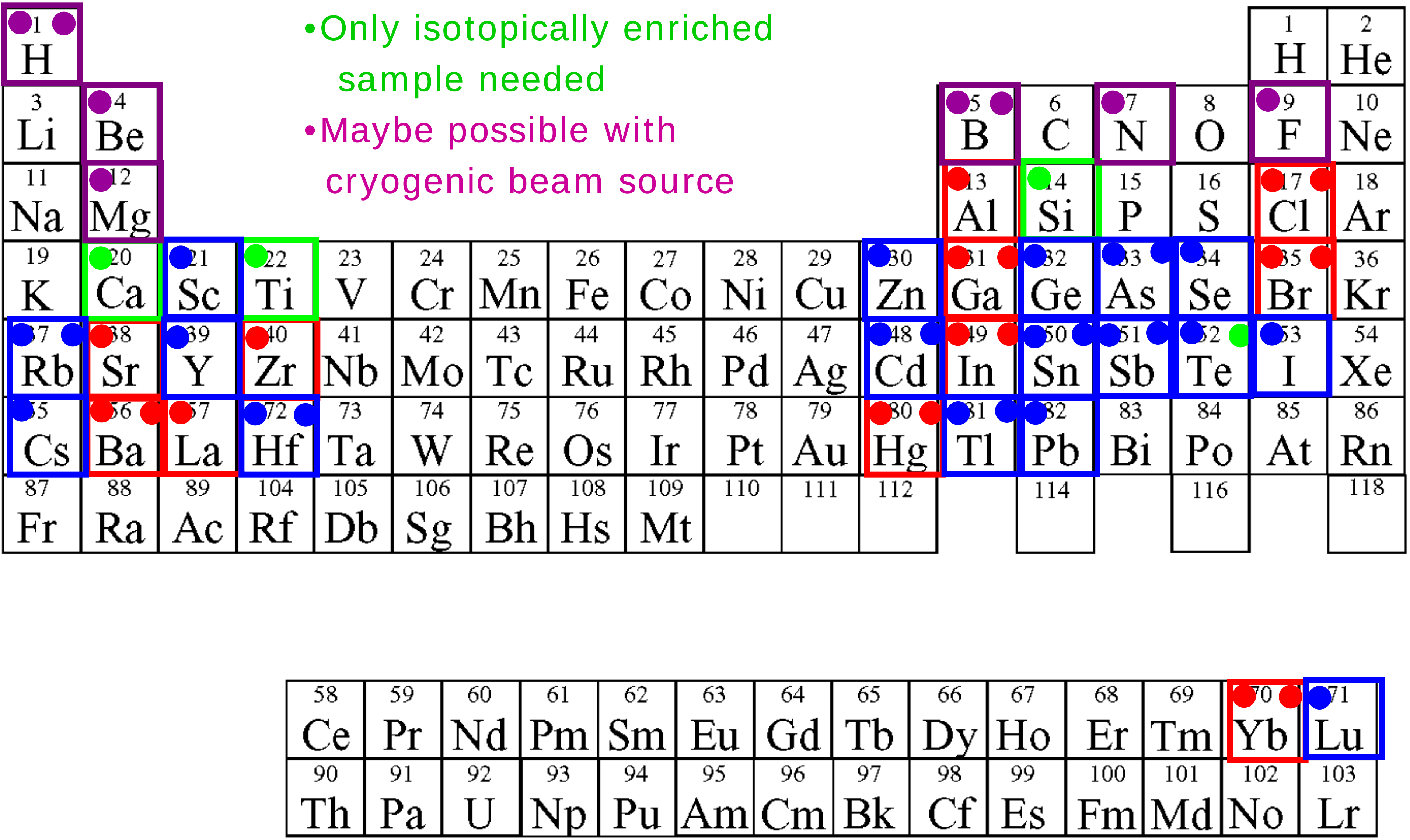
$\longrightarrow \Delta \sim 10^3$ Hz

(vs 10^{14} Hz for atoms)



Viable Nuclei For Anapole Measurement

- Everything OK (one dot/isotope)
- Only molecular spectral data needed
- Only isotopically enriched sample needed
- Maybe possible with cryogenic beam source



Chosen Molecule: ^{137}BaF

Why ^{137}BaF?

- Odd neutron (^{133}Cs had odd proton)
- Heavy → larger anapole moment
- Spectroscopy available
- BaF molecular beams had been made before
- Large enough natural abundance – don't need enriched source
- Transitions are diode laser accessible

Development & testing: ^{138}BaF

- W = 0 (no parity violation)
- Larger natural abundance (~75% vs ~11% for ^{137}Ba)
- Can use same source as ^{137}Ba

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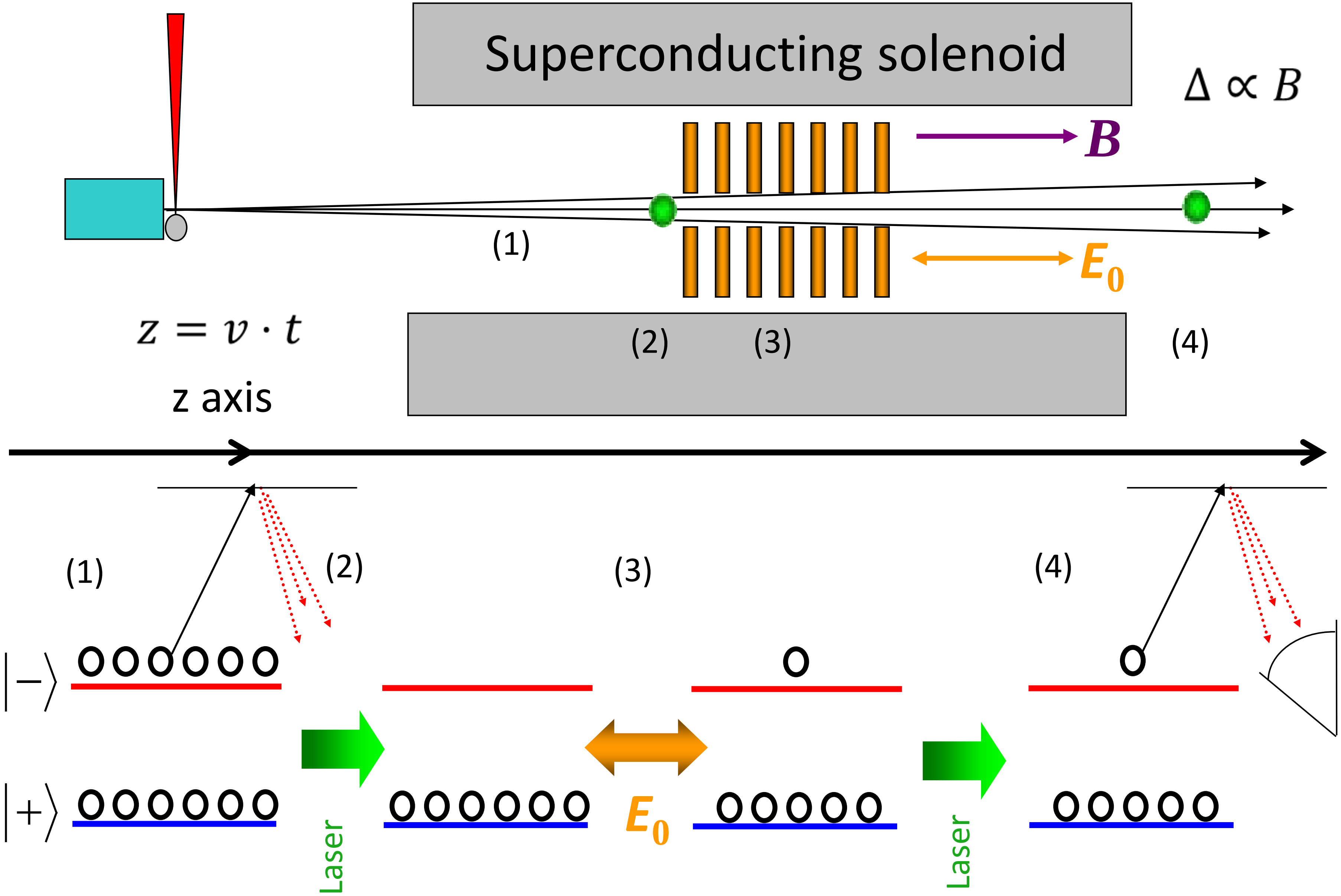
Experimental Schematic



Signal

Applied E field: $E(t) = E_0 \sin(\omega t)$

N_0: # of molecules in lower state
Δ: Detuning
d: dipole matrix element
W: weak matrix element

$$S(E_0) = 4N_0 \sin^2\left(\pi\frac{\Delta}{\omega}\right)\left[\left(\frac{dE_0}{\omega}\right)^2 + 2\frac{W}{\Delta}\frac{dE_0}{\omega} + \cancel{\frac{W^2}{\Delta^2}}\right]$$

Signal:
population of
upper (detection)
state at end

“Stark Interference” term:
without this, dependence
on W would be second order

Second order.
Very small.
Ignore.

Asymmetry

$$S(E_0) = 4N_0 \sin^2\left(\pi\frac{\Delta}{\omega}\right)\left[\left(\frac{dE_0}{\omega}\right)^2 + 2\frac{W}{\Delta}\frac{dE_0}{\omega}\right]$$

1) Measure Signal for $+E_0$ and $-E_0$

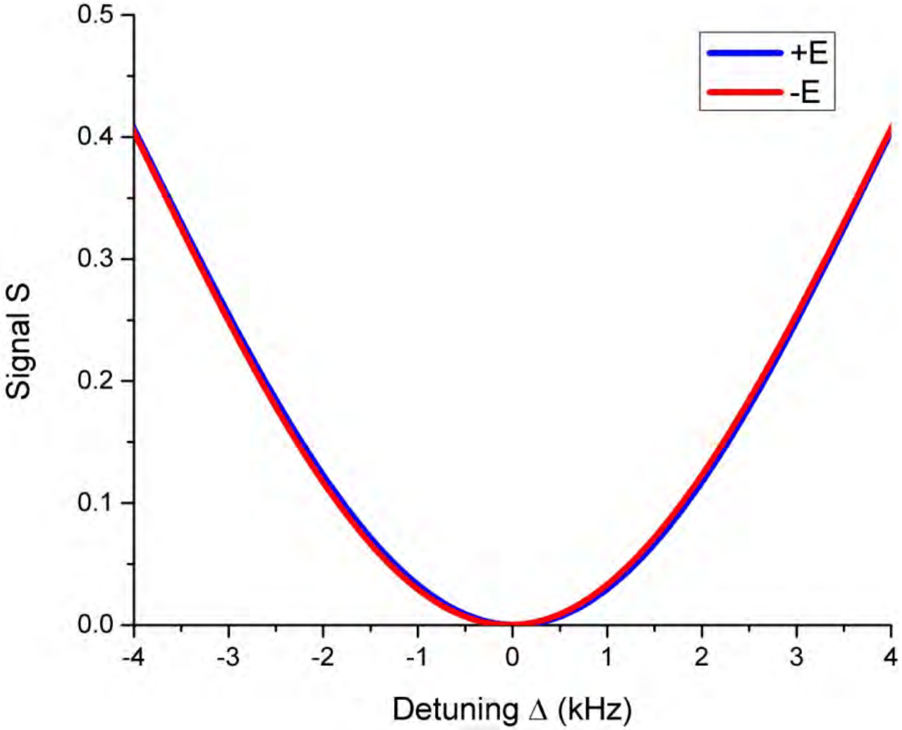
2) Form Asymmetry:

$$A = \frac{S(+E_0) - S(-E_0)}{S(+E_0) + S(-E_0)} = \frac{W}{\Delta}\cdot\frac{\omega}{dE_0}$$

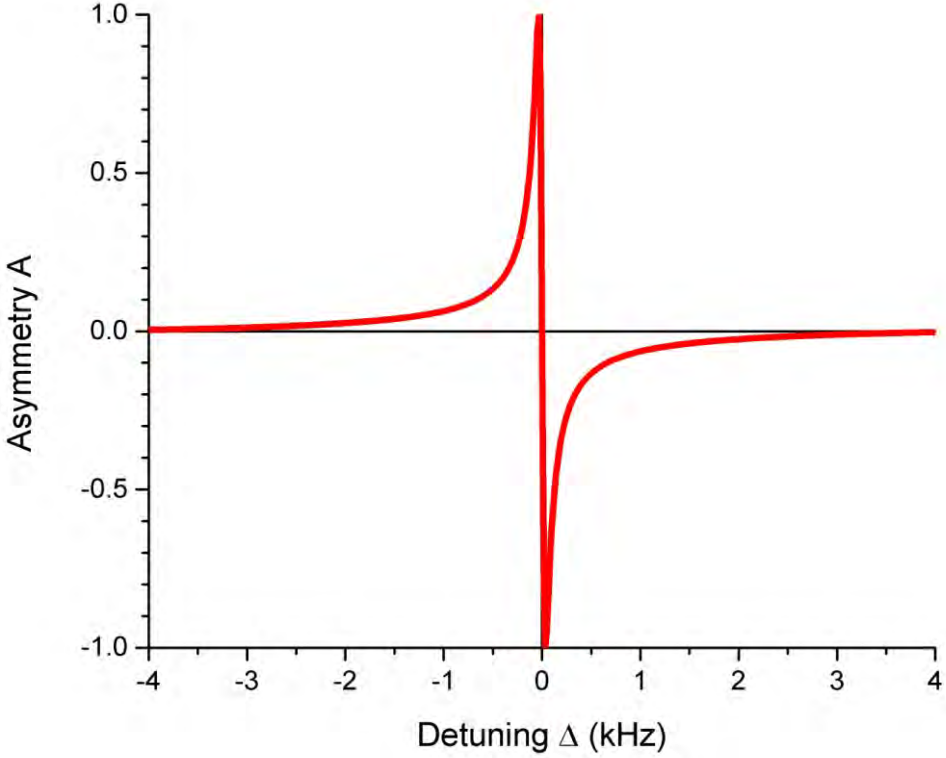
3) Solve for W in terms of known quantities.

Example Signal & Asymmetry

Signal



Asymmetry



- Calculated by numerically solving Schrodinger eqn.
- Assumes W = 5Hz

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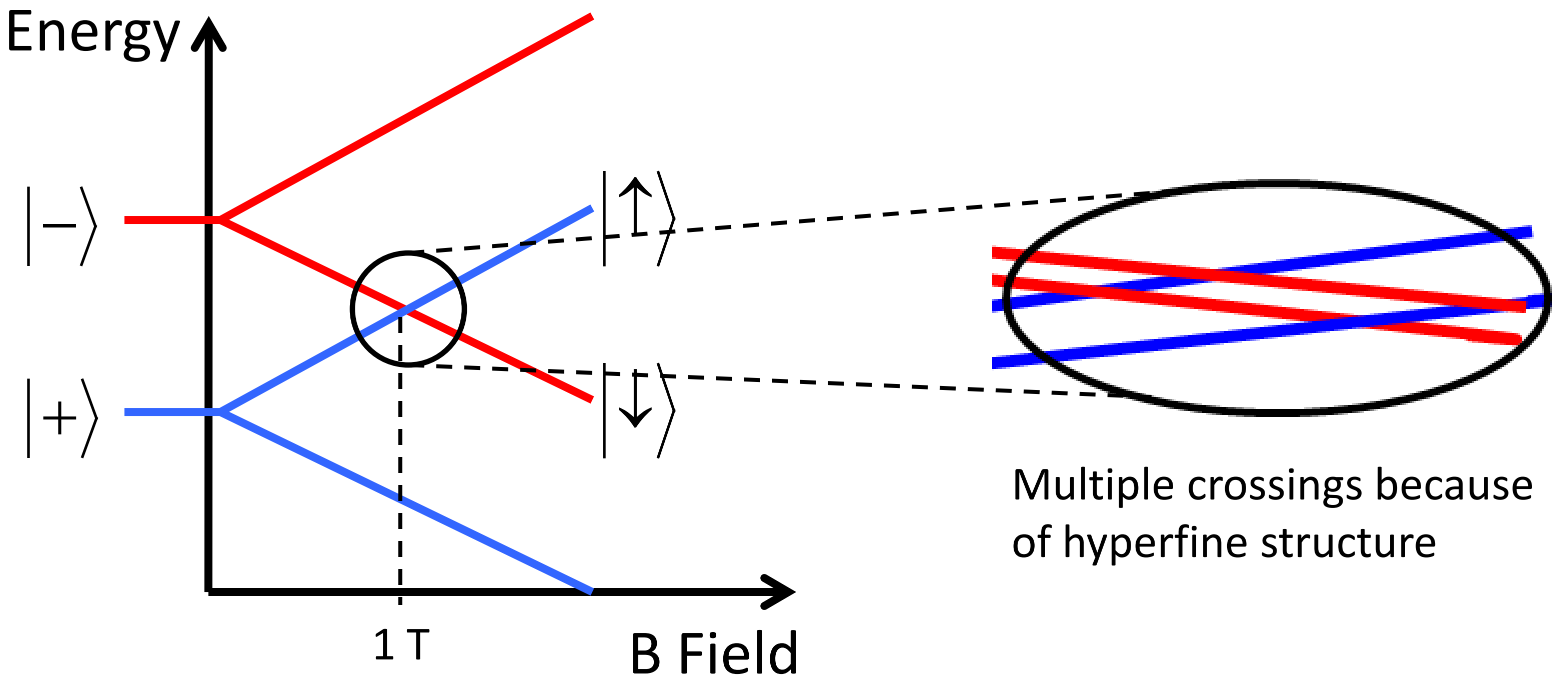
Multiple Crossings



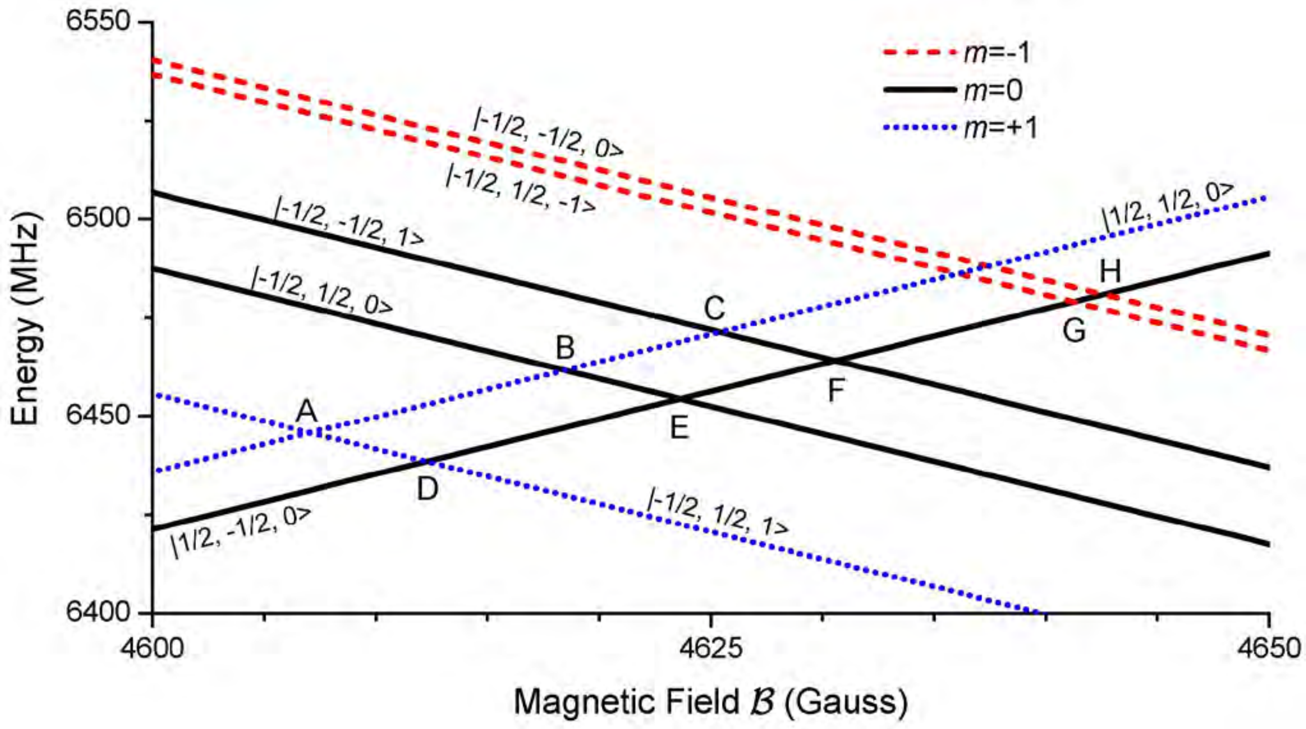
Multiple crossings because of hyperfine structure

Matrix element W is different at each crossing

Underlying PV magnitudes (κ_Z & κ_a) are same at all crossings

→ Measure at different crossings as systematic check

Level Crossing Spectroscopy in ^{138}BaF



$$\left|m_S, m_I, m_N\right\rangle$$

S: Electron spin
I: Nuclear spin
N: Molecule rotational
ang. mom.

$\hat{n}$: molecule
internuclear axis

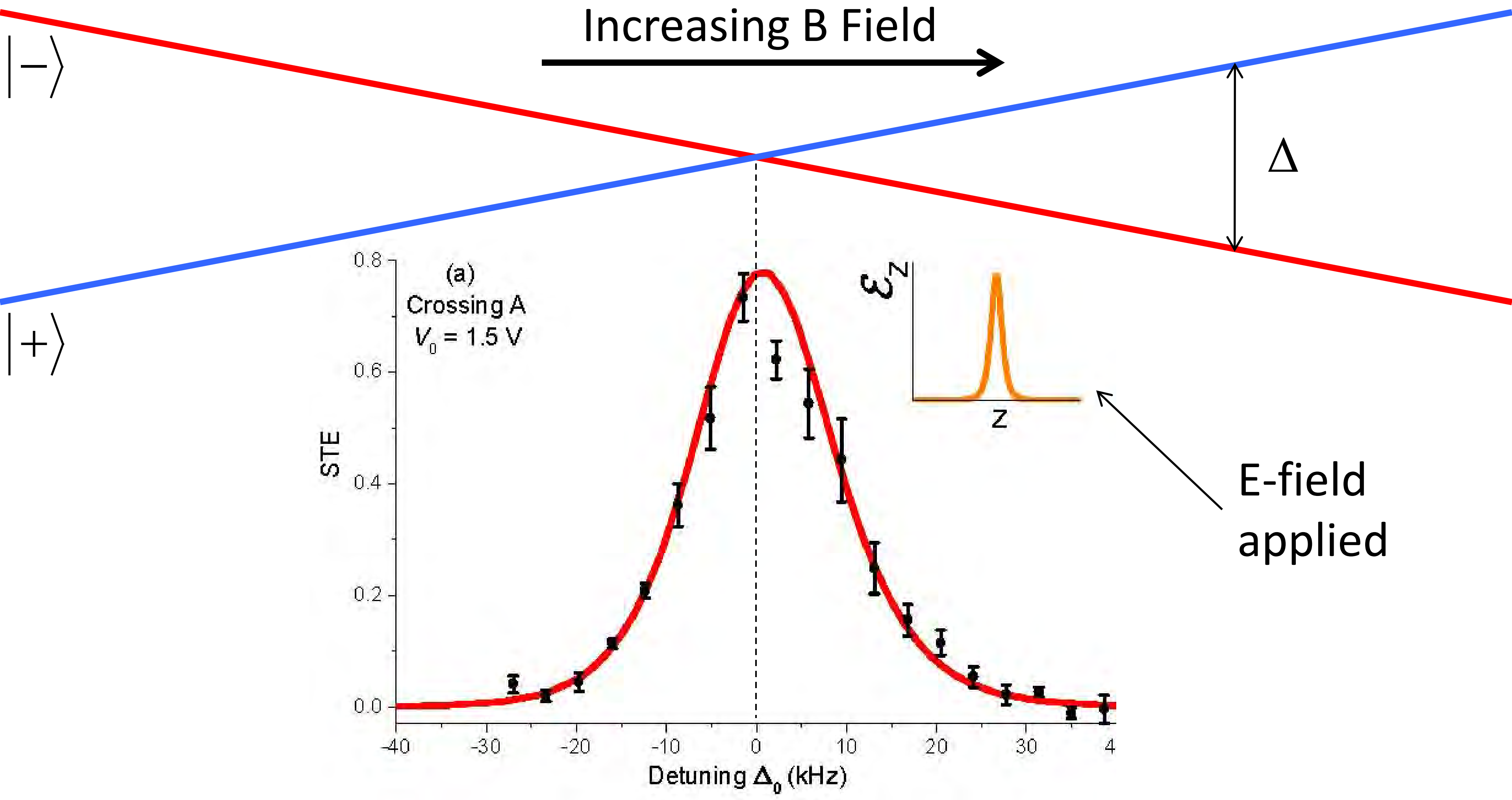
$$W \propto \underbrace{(\kappa_Z + \kappa_a)}_{}\underbrace{(\hat{n} \times \vec{S}) \cdot \vec{I}}_{} \longrightarrow$$

Angular factor.
Different for
each crossing.

PV magnitudes.
Same at all crossings

Want to measure PV at multiple crossings as systematic check
→ Need to find B field values where levels cross

Finding Crossing Locations



Increasing B Field

$|-\rangle$

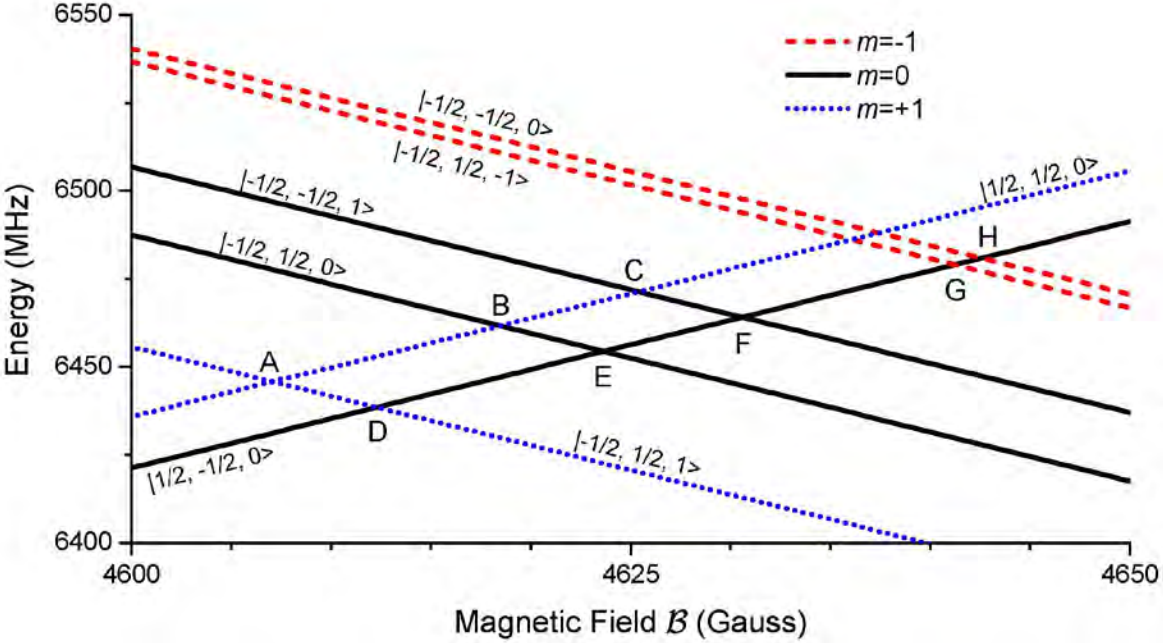
$|+\rangle$

Δ

E-field applied

Maximum signal occurs when B-field is set such that Δ=0

Spectroscopy Results



Crossing			$\mathcal{B}_0$-4600	
X	m	m'	Meas.	Fit
A	1	1	04.841(2)	04.777
B	1	0	16.136(2)	16.050
C	1	0		
D	0	1		
E	0	0	21.259(2)	21.240
F	0	0	28.214(2)	28.278
G	0	-1	38.671(2)	38.667
H	0	-1	40.069(2)	40.178

"Zeeman-tuned rotational level-crossing spectroscopy in a diatomic free radical"
S.B. Cahn et. al.
arXiv: 1310.6450

Soon to be in PRL

Also measured:
- Dipole matrix elements (d)
- Polarizabilities (α)
- Lineshapes

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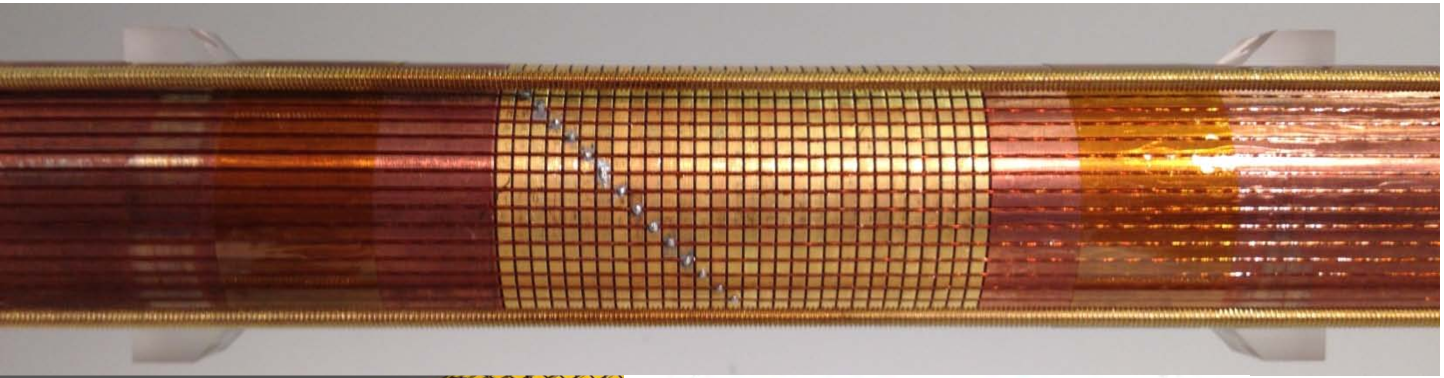
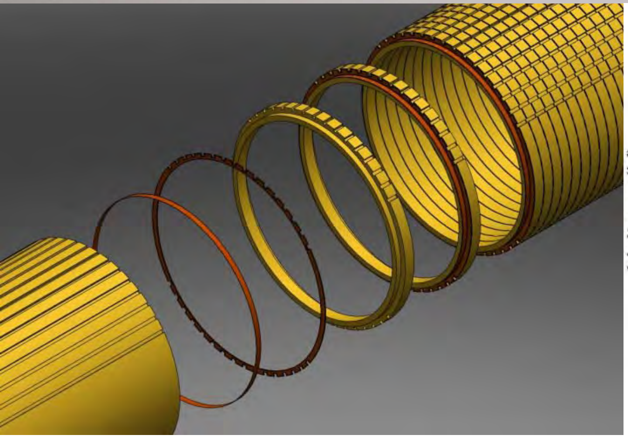
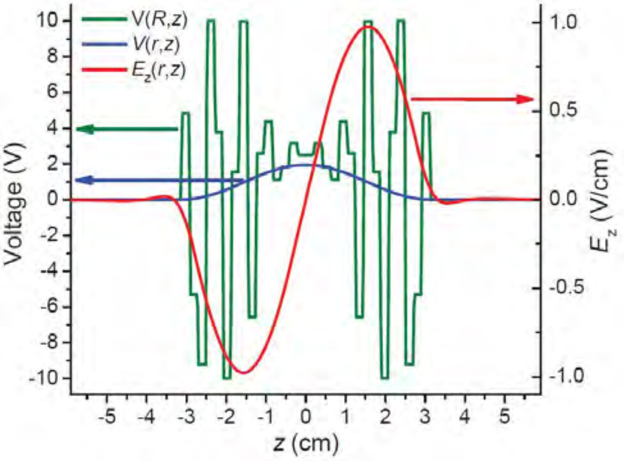
New Interaction Region

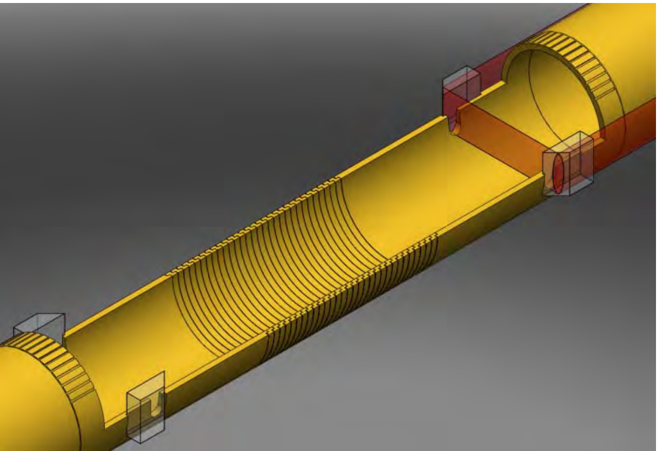






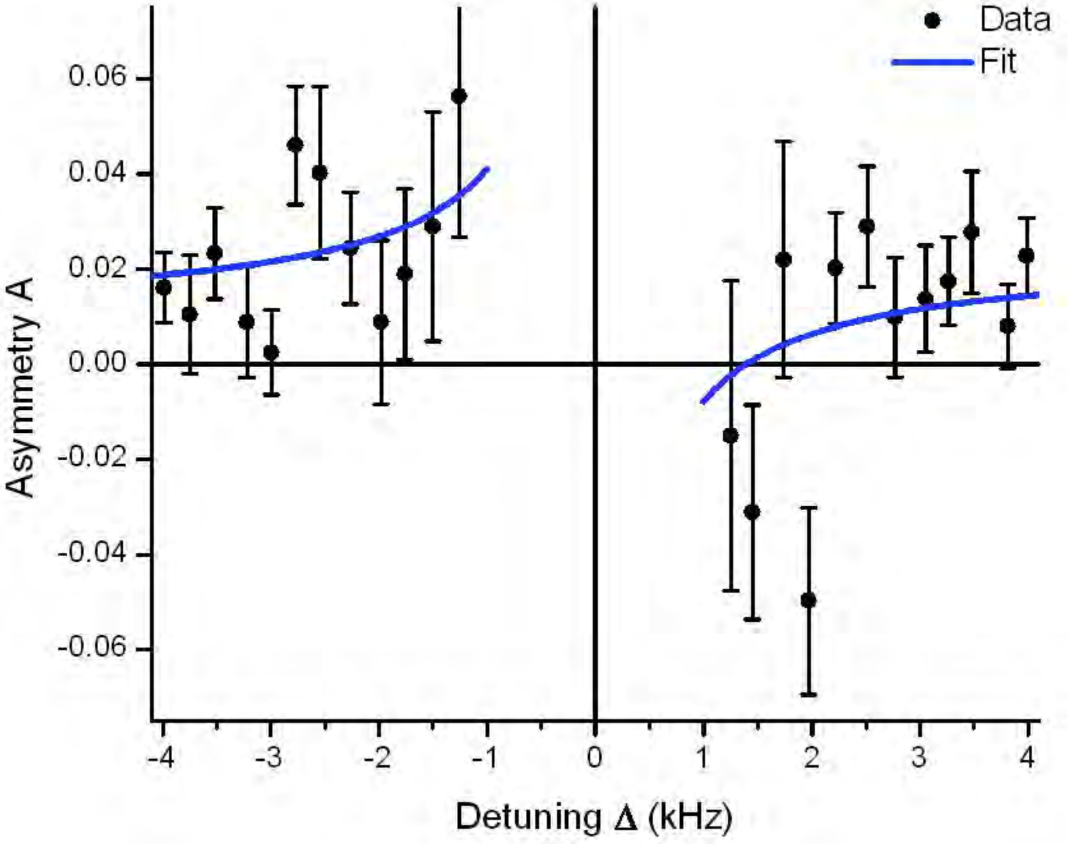
- Old interaction regions: 2 electrodes, 7 electrodes

- New interaction region: 32 electrodes
→ better control over E field
→ **one cycle sine wave for PV measurement**



- Prisms allow laser delivery for state preparation

First PV Data with ^{138}BaF



- ^{138}Ba Expected:
  W = 0

- Measured:
  W = -5.5   2.6 Hz (stat)

- ~2.5 hours of data

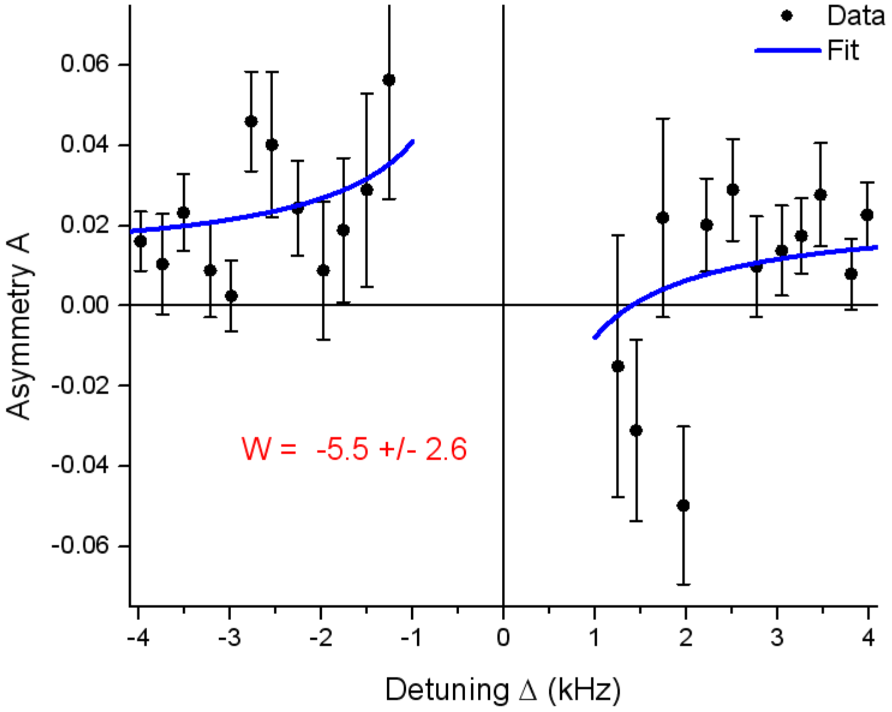
- Previous best sensitivity:
  2.9 Hz in 30 hours with atomic Dy*

- Measured W due to systematic effects

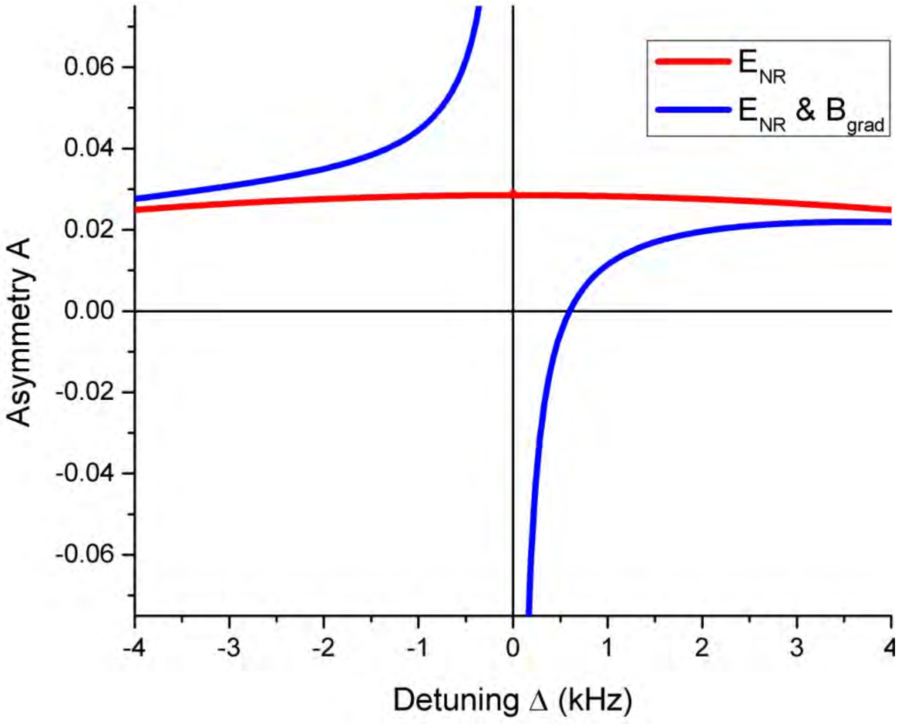
*Nguyen, Budker, DeMille, & Zolotorev, PRA **56**, 3453 (1997)

Evidence of Systematics

Data



Numerical Calculation



- Non-reversing E field (E_{NR}) ⟶ even part of Asymmetry (e.g. vertical offset)
- E_{NR} + B gradients (B_{grad}) ⟶ odd part of Asymmetry (looks like parity violation!)
- Need to measure & then eliminate E_{NR} & B_{grad}

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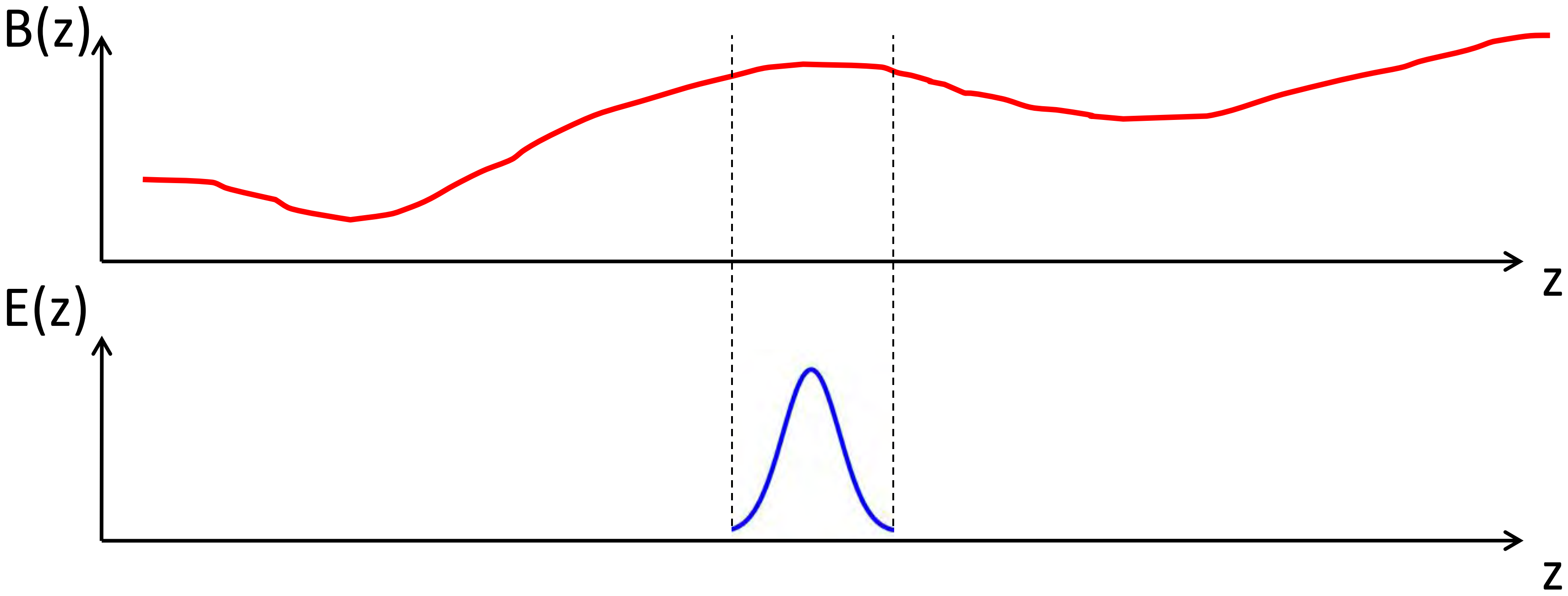
B field Measurement w/ Molecule Signal

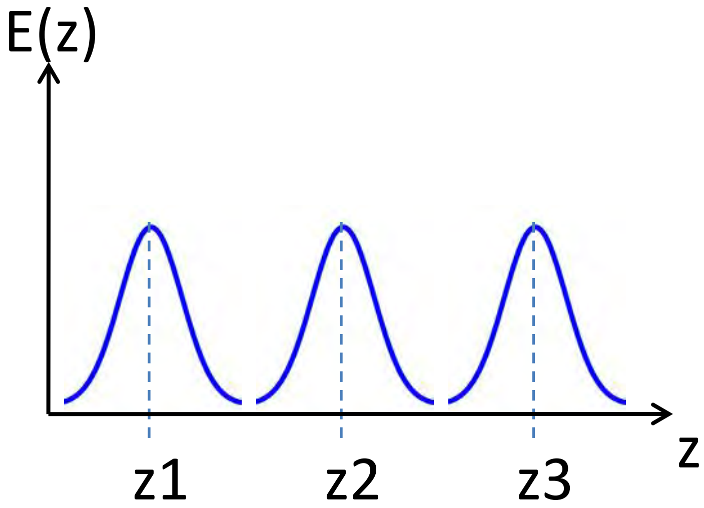
Want to “flatten” B field so that it is uniform
→ Must measure B field first



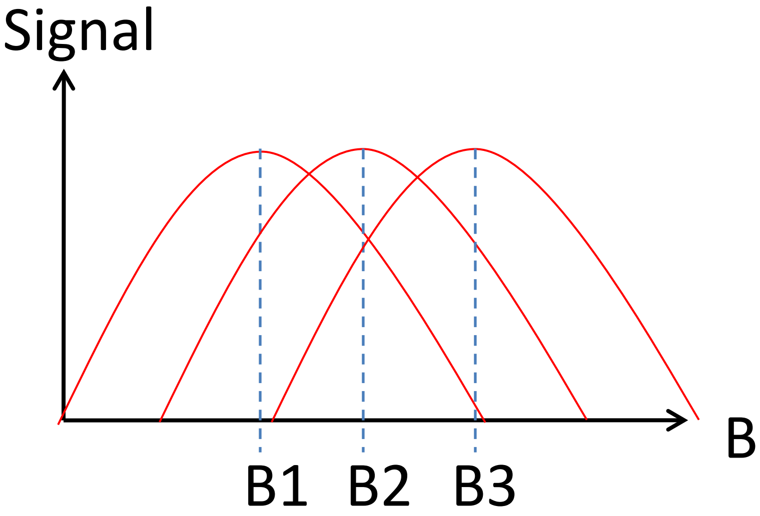
B field only matters where E is non-zero

→ Measure B(z) by translating E pulse across z and recording Signal

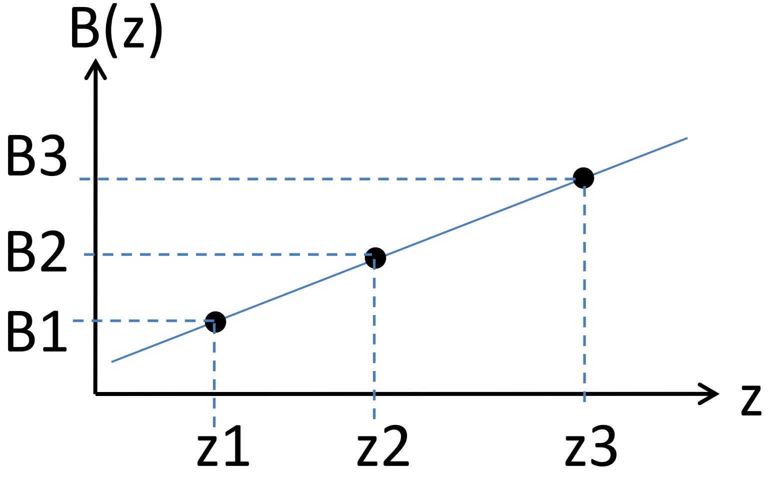
B field Measurement w/ Molecule Signal



Apply E-field

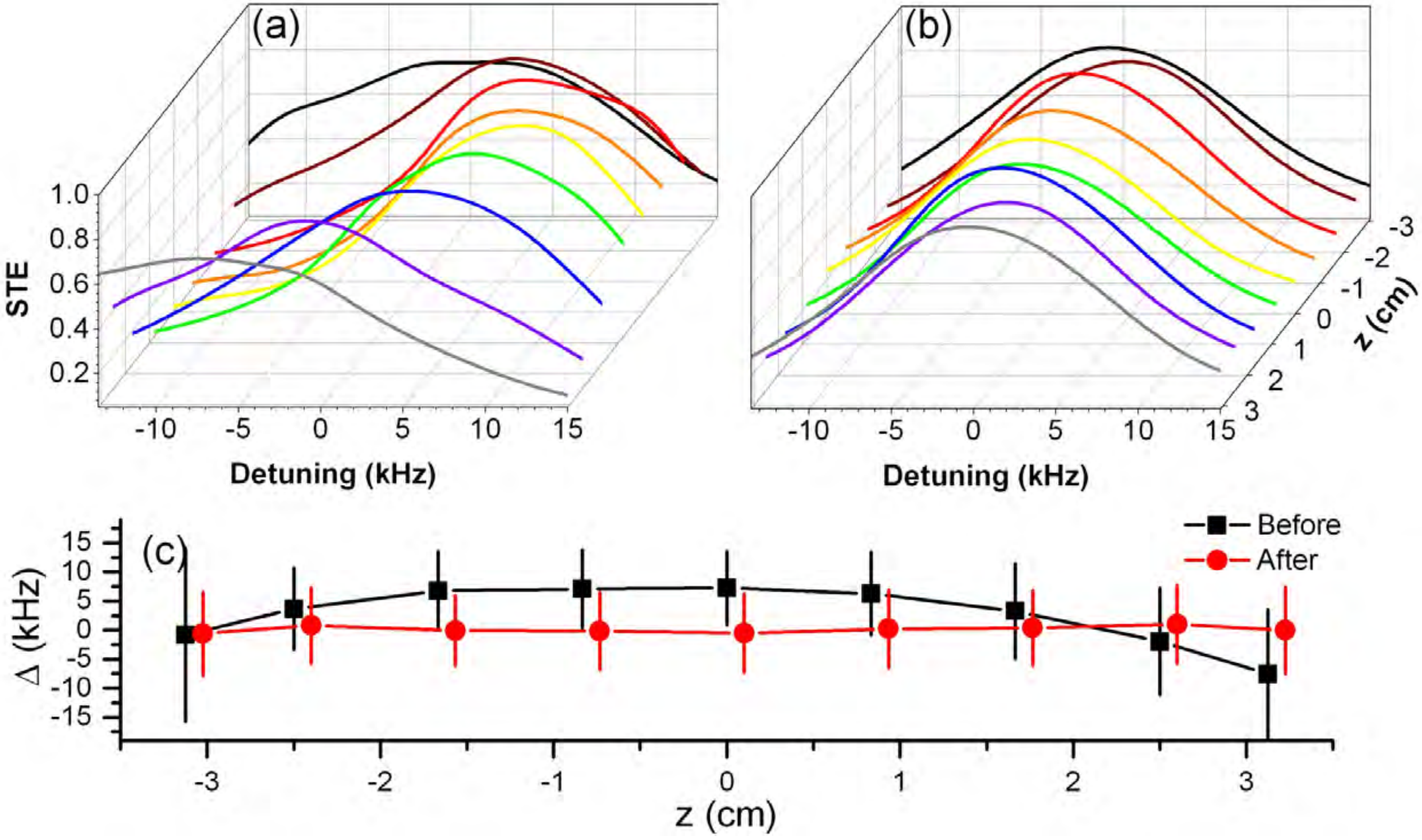


Find signal maximum
(i.e. $\Delta = 0$)



Repeat across
interaction
region to get B(z)

B field Shimming

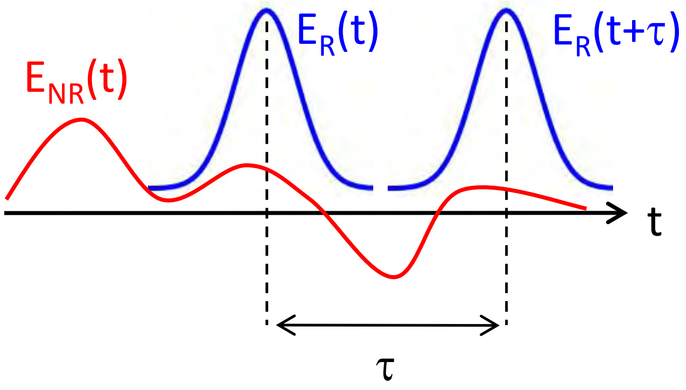


- B field measured (a)
- Shim coils adjusted to flatten field
- B field measured again (b)

E Field Measurement w/ Molecule Signal

$$c_- \propto \int E(t) e^{-i\Delta t} dt$$
$$\propto E(\Delta)$$

1st order perturbation theory
(F.T. of E(t))



$$c_- \propto E_{NR}(\Delta) + E_R(\Delta)$$

$$c_- \propto E_{NR}(\Delta) + e^{i\Delta\tau} E_R(\Delta)$$

shifted E_R

$$S \propto |E_{NR}(\Delta)|^2 + |E_R(\Delta)|^2 + \underbrace{E_R(\Delta)\left[\mathrm{Re}[E_{NR}(\Delta)]\cos(\Delta\tau) - \mathrm{Im}[E_{NR}(\Delta)]\sin(\Delta\tau)\right]}_{\text{Interference term}}$$

$$\underbrace{S(+E_R) - S(-E_R)}_{\text{“Signal Difference”}} \propto 2E_R(\Delta)\left[\mathrm{Re}[E_{NR}(\Delta)]\cos(\Delta\tau) - \mathrm{Im}[E_{NR}(\Delta)]\sin(\Delta\tau)\right]$$

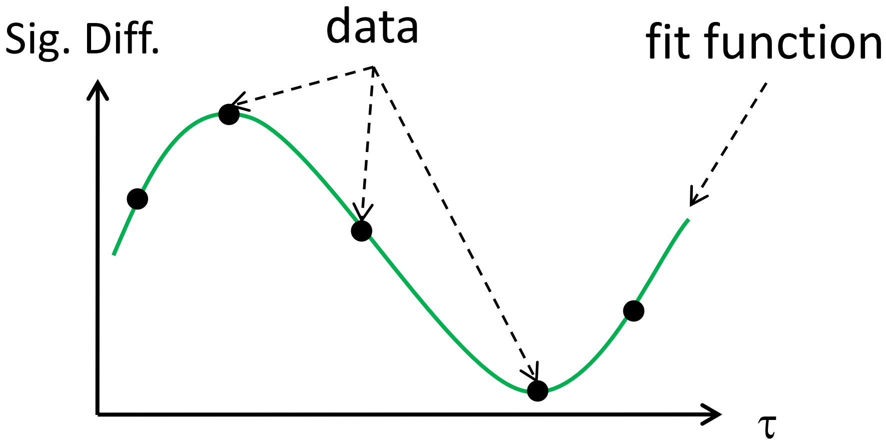
E Field Measurement w/ Molecule Signal

- Set Δ = constant
- Take data over range of τ (applied E location)

2 fit parameters: (a, b)

$$\underbrace{S(+E_R)-S(-E_R)}_{\text{from data}} \propto \underbrace{2E_R(\Delta)\left[\overbrace{\mathrm{Re}[E_{NR}(\Delta)]}\cos(\Delta\tau)-\overbrace{\mathrm{Im}[E_{NR}(\Delta)]}\sin(\Delta\tau)\right]}_{\text{fit function:}}$$

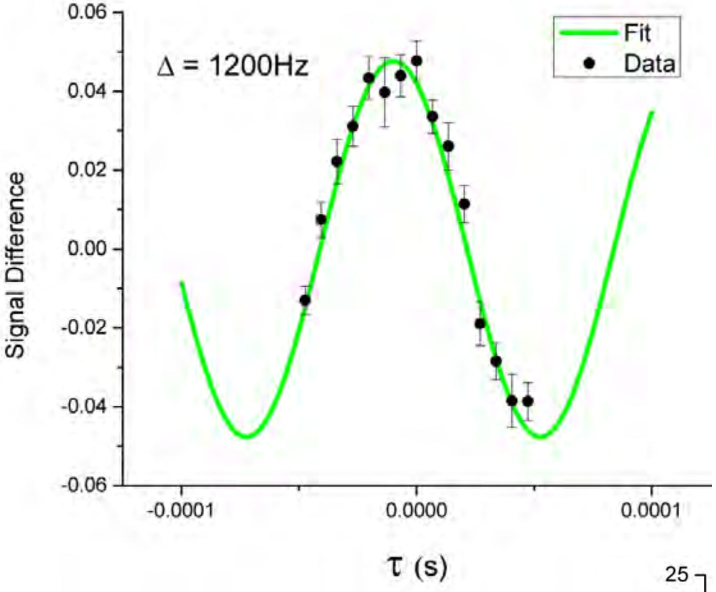
$$a * \cos(\Delta\tau) + b * \sin(\Delta\tau)$$



- Repeat at a range of Δ to construct $E_{NR}(\Delta)$
- Fourier transform to get $E_{NR}(t)$

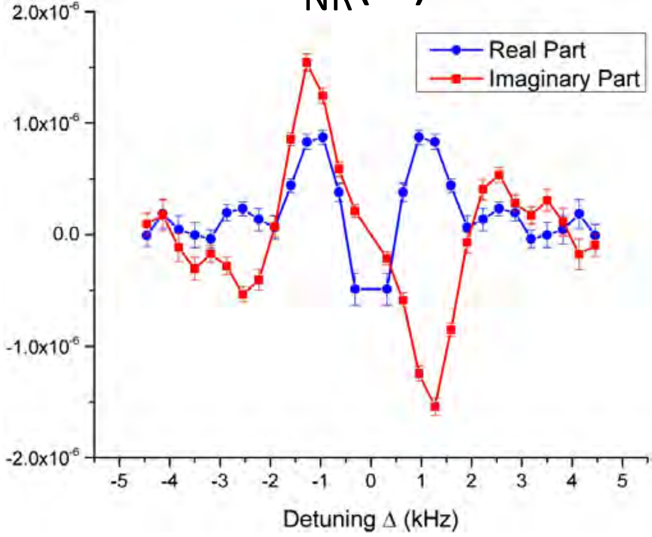
E_{NR}(t) Measurement Example

Interference Term Fit



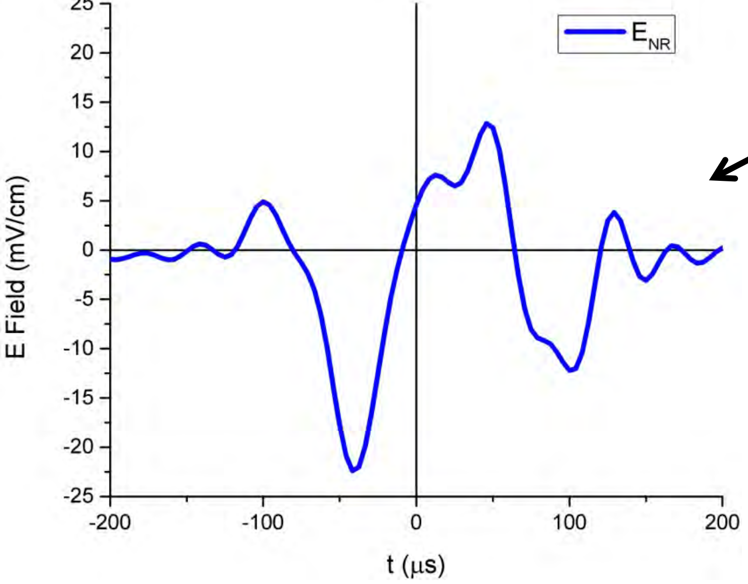
Repeat over range of Δ

$E_{NR}(\Delta)$

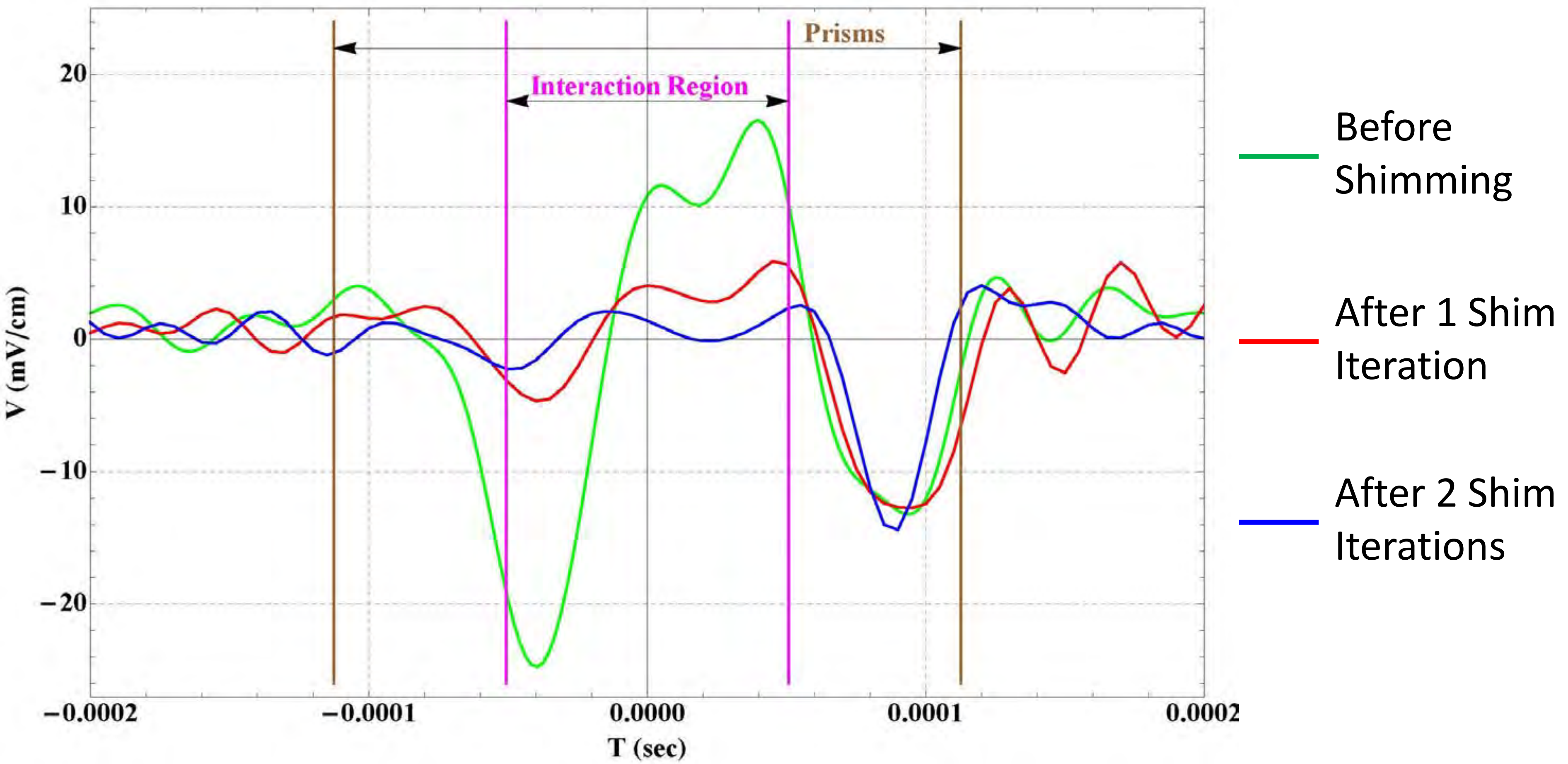


Fourier Transform

E_{NR}(t)



$E_{NR}(t)$ Shimming Results



"Shimming" = Applying voltages to counteract E_{NR}

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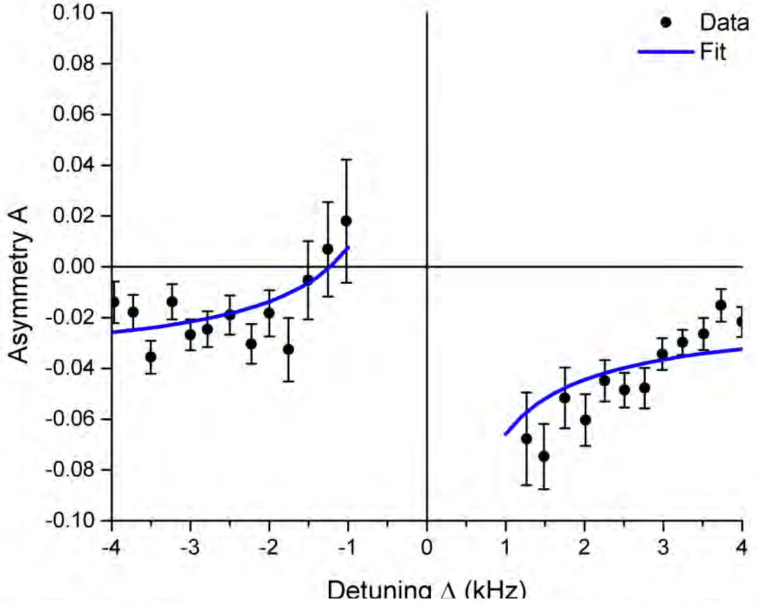
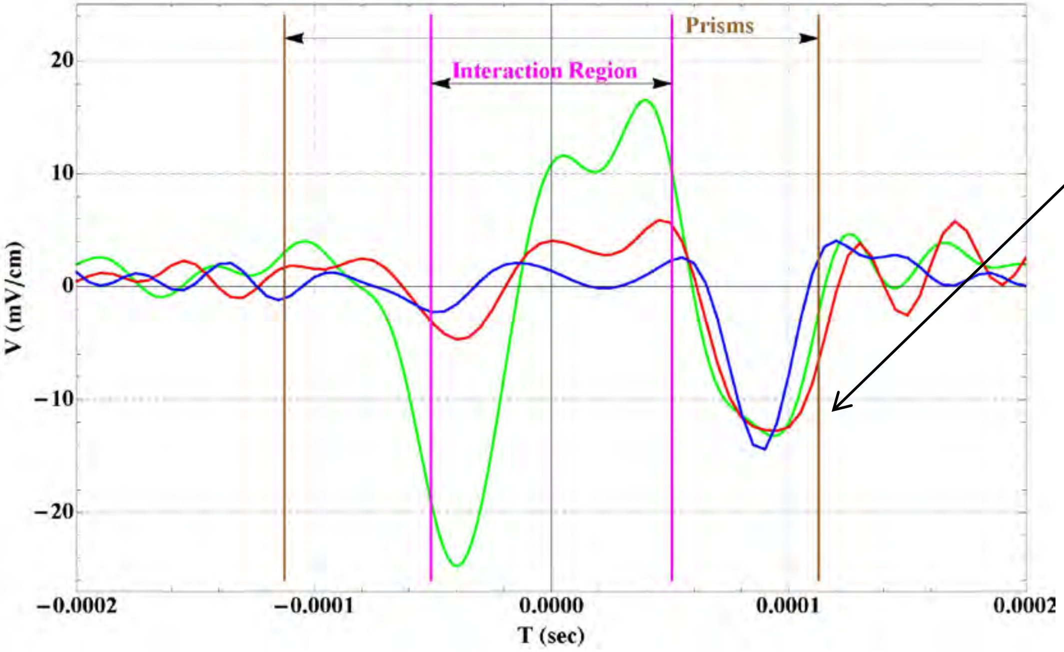
Recent Data



Measured:

W = -8.2 1.2 Hz (stat)

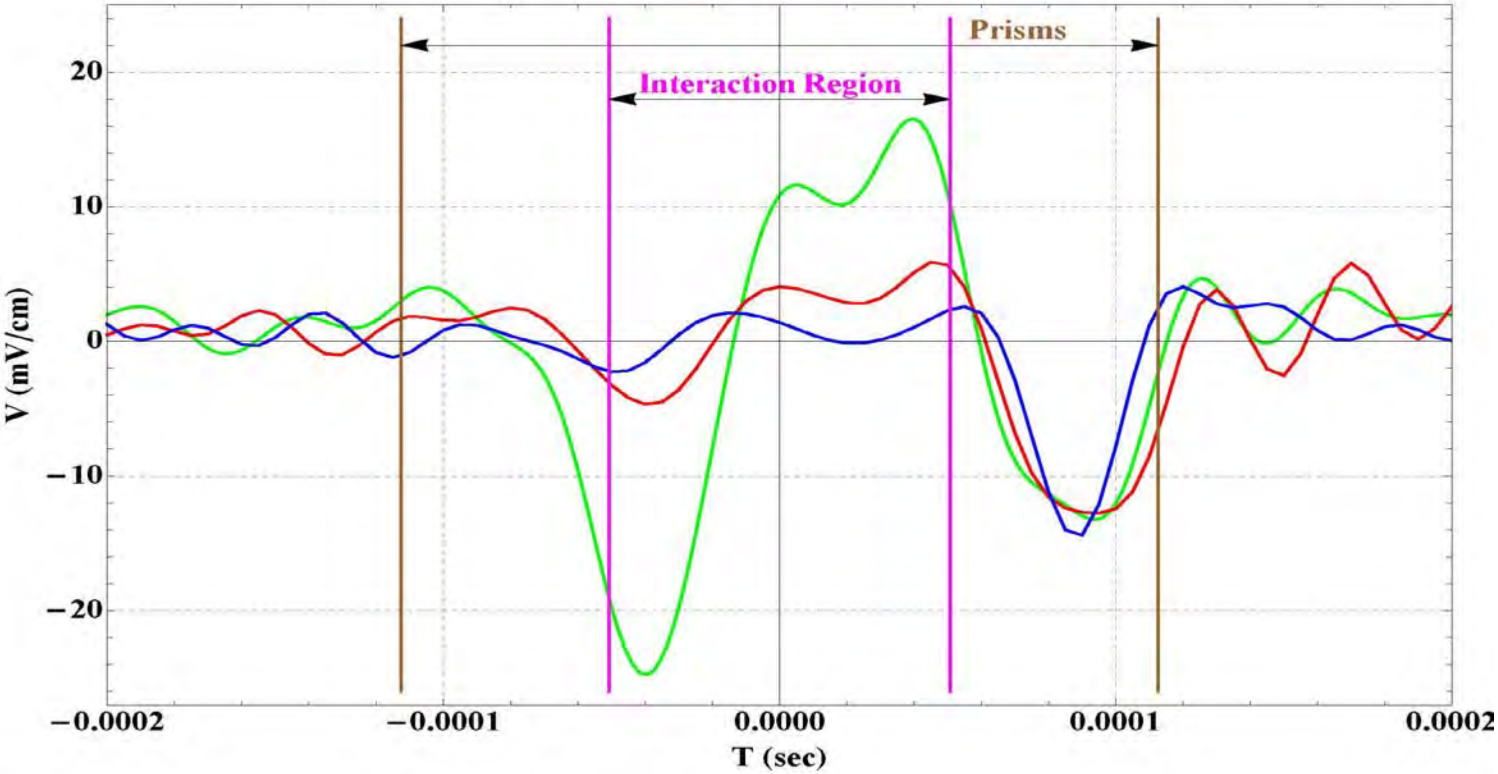
Why do systematics remain?

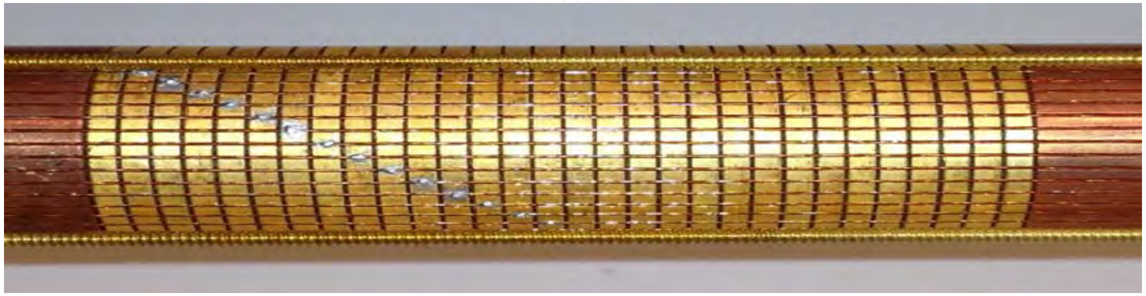


Part of E_{NR} lies outside interaction region
→ can't be shimmed out

Numerical calculations:
This E_{NR} plus reasonable B_{grad} still gives large W

Longer E-field Region





Plan: Lengthen electrodes

→ can shim E fields and measure B fields further out

Future Work

- Make new interaction region with longer electrodes
- Shim out E_{NR} and B_{grad}
- Measure PV in ^{138}BaF (Should be zero)
- Improvements in signal (hexapole lens, cryogenic source)
- Measure PV in ^{137}BaF (Expected W ~5Hz)