Progress Towards Measurement of the Nuclear Anapole Moment of ^{137}Ba Using BaF Molecules

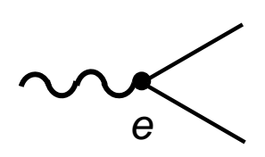
Sidney Cahn, Emine Altuntas, Jeffrey Ammon, David DeMille
Yale University

Jai-Min Choi
Chonbuk National University

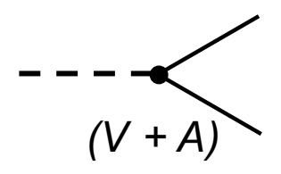
Motivation and Potential Impact

•Goal: Measure nuclear spin dependent parity violating (**NSD-PV**) effects

•Strength of interactions: charges.
Example: electron charge → EM strength:



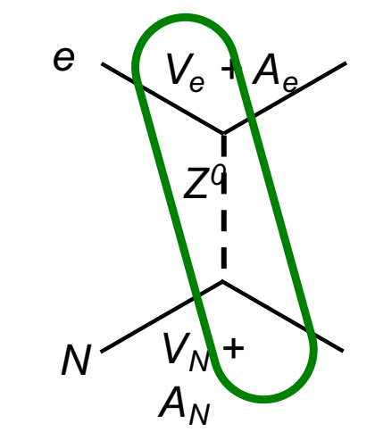
•Weak interactions: two charges:



$\hat{P}$: parity operator
V : vector $\left(\hat{P}V = -V\right)$
A : axial vector $\left(\hat{P}A = A\right)$

•Two primary contributions to NSD-PV:

1) Z^0 Boson Coupling



•Potential ~*30%* measurement of electron-nucleon coupling (previous experiments: *70%, 300%*)

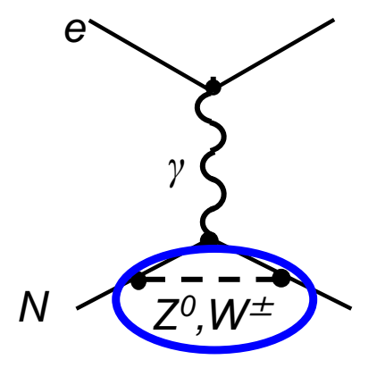
$$\propto \cancel{V_e} V_N + \cancel{A_e} A_N + \boxed{V_e A_N} + \cancel{A_e} V_N$$

Hard to measure against EM bgnd Parity even.

Nuclear spin dependent, parity violating. Hard to calculate in SM (renormalized by QCD)

"weak charge" Already well measured, does not contribute here.

2) Nuclear Anapole Moment



- Z^0 and $W^\pm$ exchange within nucleus gives rise to **nuclear anapole moment**
- Useful to check nuclear calculations needed to interpret **neutrinoless double beta decay** measurements.

•Resultant effective term in the Hamiltonian:

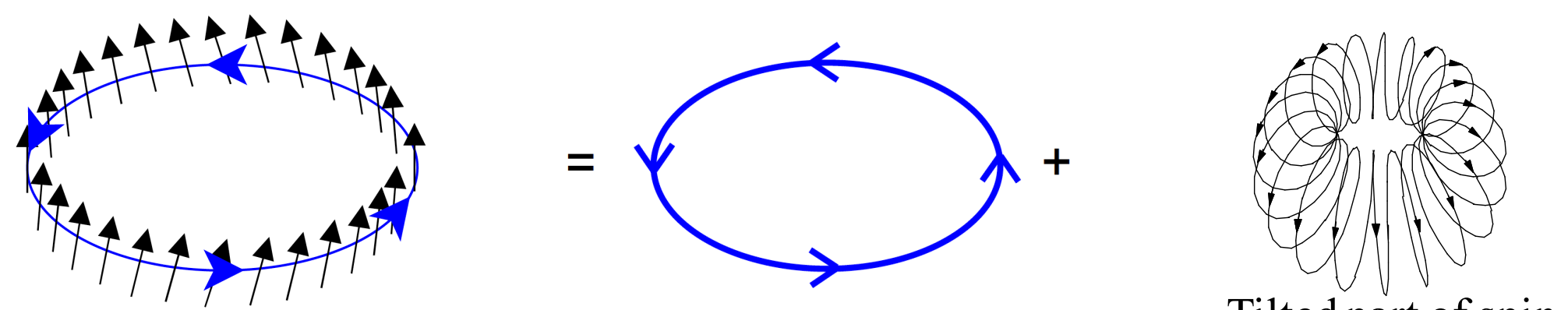
$$\hat{H}_P = \left(\kappa_a + \kappa_Z\right)\frac{G_F}{\sqrt{2}}\frac{(\vec{\sigma}_e\cdot\vec{p})(\vec{\sigma}_e\cdot\vec{I})}{I}\delta^3(\vec{r})$$

κ_a: strength of anapole term
κ_Z: strength of Z^0 coupling term
G_F: Fermi constant
σ_e: electron spin
p: electron momentum
I: nuclear spin

$\kappa_a \propto A^{2/3}$
κ_Z constant w.r.t A
(A: nuclear mass)

→ Could distinguish anapole and Z^0 effects via measurements over range of nuclei

What Is the Nuclear Anapole Moment?



PV electroweak interactions inside nucleus ⟶ nucleon spin tilted in direction of motion

Orbital angular momentum + nucleon spin ⟶ current loop

Tilted part of spin
↓
toroidal current
=
Anapole moment

Measurement Strategy

Parity Violation

•NSD-PV mixes opposite parity states → states lose definite parity:

$$|even\rangle \rightarrow |even\rangle + \underbrace{\frac{\langle even|H_P|odd\rangle}{E_{odd}-E_{even}}\cdot|odd\rangle}_{1^{st}\text{ order pert. thy.}}$$

•**Diatomic molecules** and **Zeeman tuning** ⟶ smaller energy difference

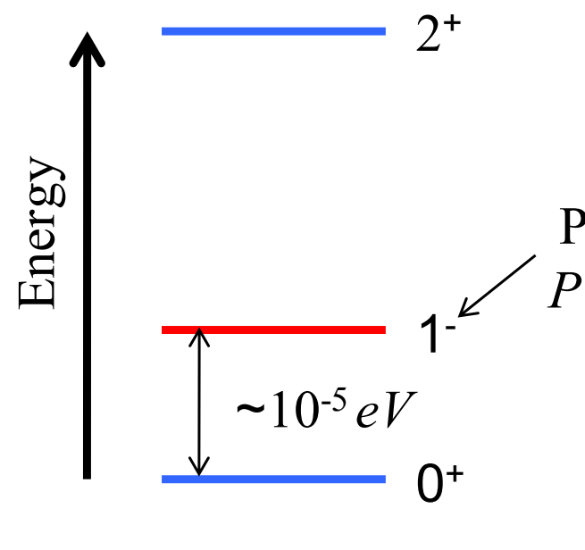
•$(E_{odd} - E_{even})$ ⟶ mixing amplified

•**Stark interference** ⟶ mixing detected

Diatomic Molecules

•**Closely spaced rotational energy levels** due to large moment of inertia

•**States alternate in parity vs J:**
- **P = (-1)^J**



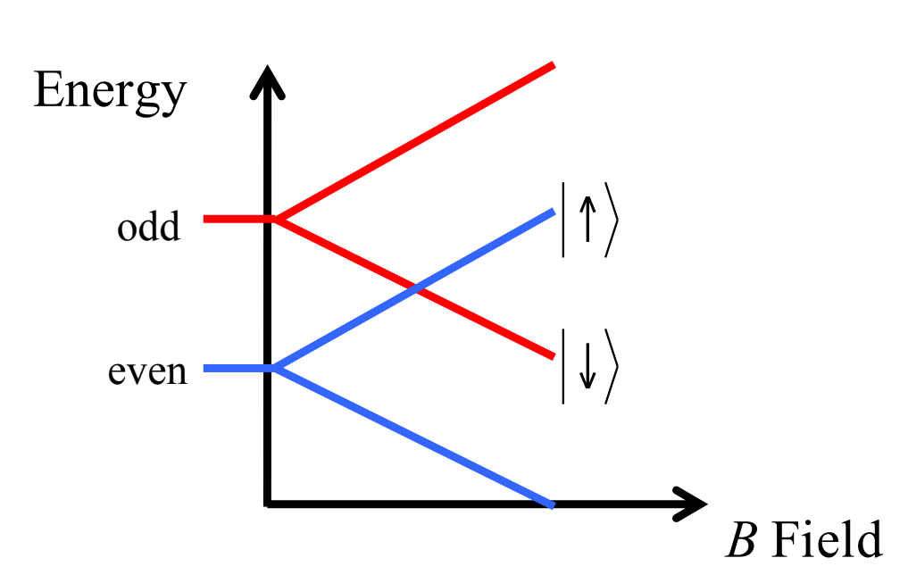
(^{133}Cs experiment: ~1eV)

Zeeman Tuning

•Levels already close → Field required to bring to crossing:

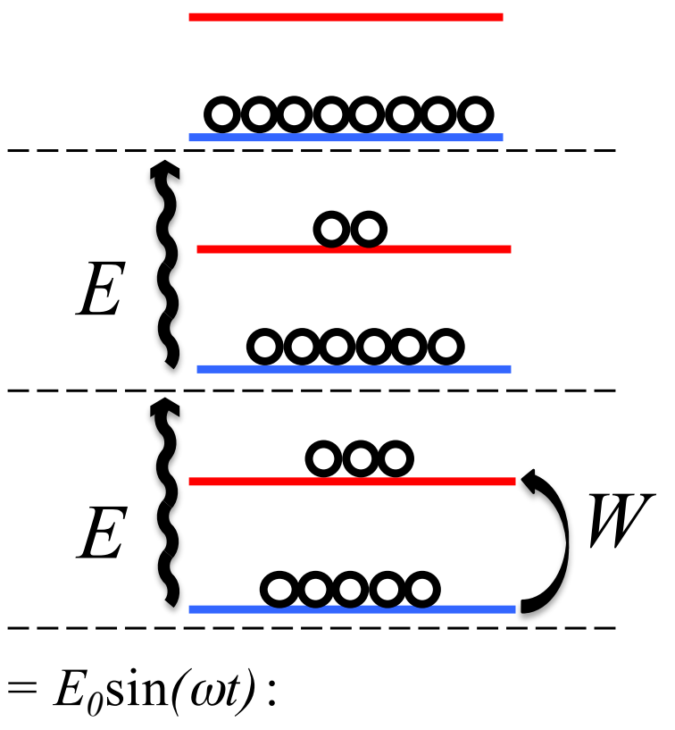
$$B = \left|\frac{\Delta E}{\mu_e}\right| \approx \frac{10^{-5}\,\text{eV}}{10^{-5}\,\text{eV/T}} \sim 1\,\text{T}$$

•Electron mag. moment μ_e is largest μ in molecule → spin up states rise in energy, spin down states fall:



Measurement Strategy, continued

Stark Interference



•Start with only lower state populated

•Drive population to upper state with *weak, far blue-detuned E* field

•NSD-PV modifies amount of population driven

•With a single cycle sinusoidal electric field of period, T, $E(t) = E_0\sin(\omega t)$:

$$H = \begin{pmatrix} 0 & iW + dE \\ -iW + dE & \Delta \end{pmatrix}$$

W: NSD-PV matrix element
E_0: E field magnitude
d: dipole matrix element
ω: E field frequency
Δ: level splitting

Population transfer: $S(E_0) \propto \left(\frac{dE_0}{\omega}\right)^2 + 2\frac{W}{\Delta}\frac{dE_0}{\omega} + \cancel{\frac{W^2}{\Delta^2}}$

•Run experiment again with $E_0 \rightarrow -E_0$

•Subtract two runs and normalize to get "asymmetry":

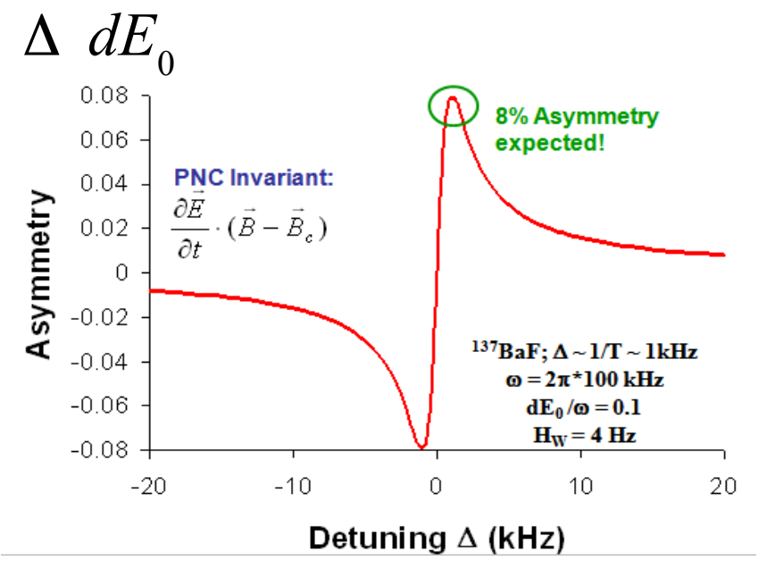
$$A = \frac{S(E_0) - S(-E_0)}{S(E_0) + S(-E_0)} = 2\frac{W}{\Delta}\frac{\omega}{dE_0}$$

•Solve for W to get NSD-PV strengths

•Shot noise uncertainty:

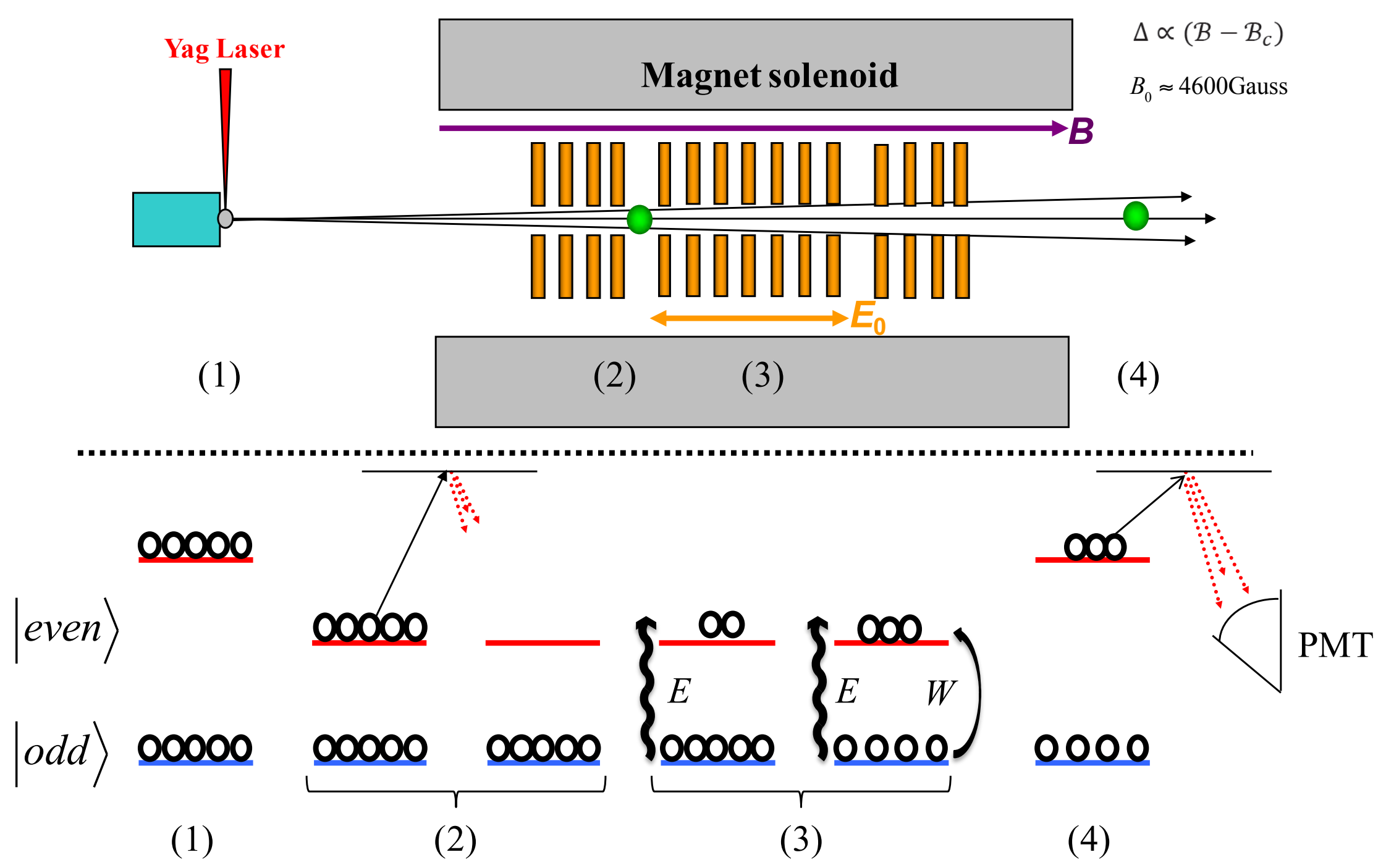
$$\delta W \approx \frac{1}{2T\sqrt{2N_0}}$$

<8 hrs integration expected for 10% uncertainty



Simulated asymmetry signal for ^{137}BaF

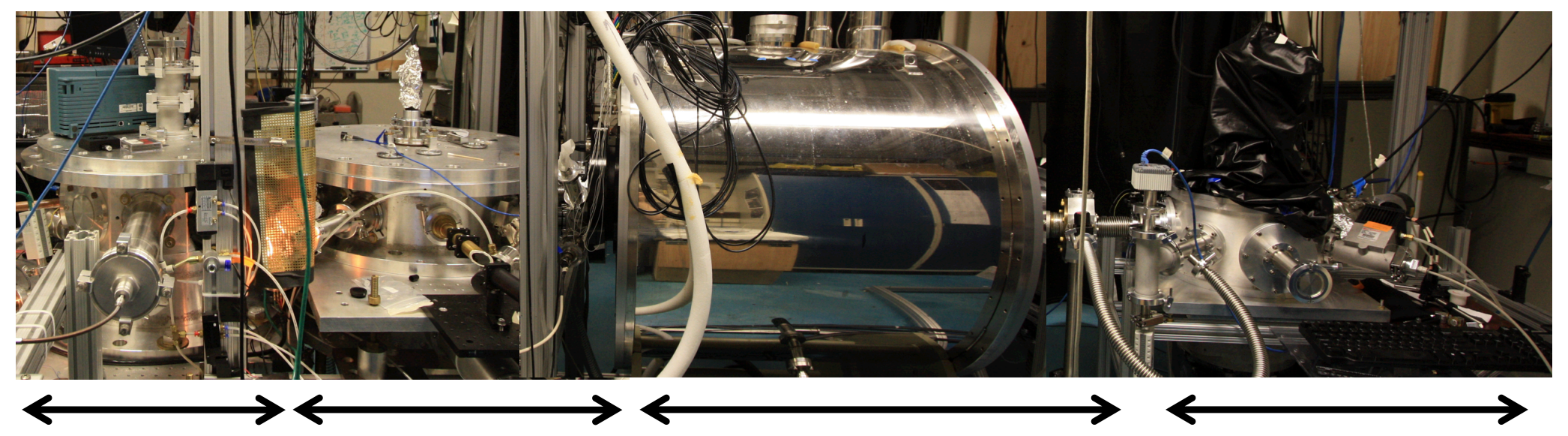
The Experiment



1) Molecular beam created. State populations equal.
2) Molecules enter B field. Upper state depleted with laser.
3) Molecules travel through electrodes. E field static in lab frame, but time varying in molecule frame. Some population driven to upper state.
4) Upper state excited by laser, fluorescence detected by PMT.

•W derived from upper state population, and NSD-PV strengths derived from W.

Experimental Apparatus



Beam source

•Solid barium rod provides ^{138}Ba (~70%) and ^{137}Ba (~10%)

•Nd:YAG ns pulsed laser ablates barium

•Pulse of Ar + SF$_6$ creates molecular beam

State preparation

•860nm diode laser empties lower (even) state

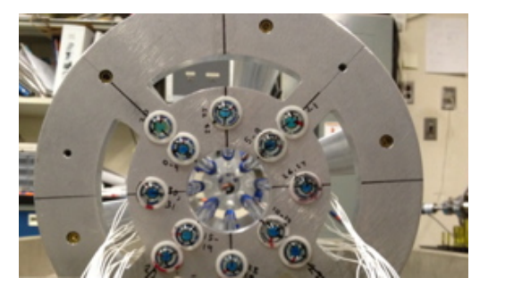
•State preparation done when molecules inside the magnet

Superconducting magnet

•Maximum field: 2T

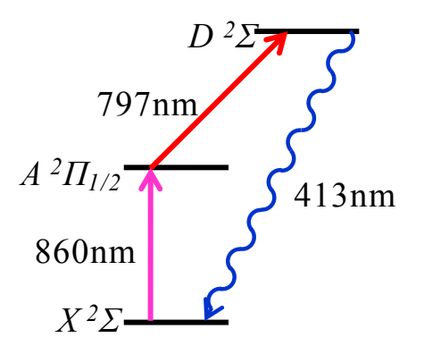
•Homogeneity: 20 ppb over 5 cm

•32 homemade NMR probes situated around beam line for B field monitoring and shimming:



State detection

•2 stage excitation:

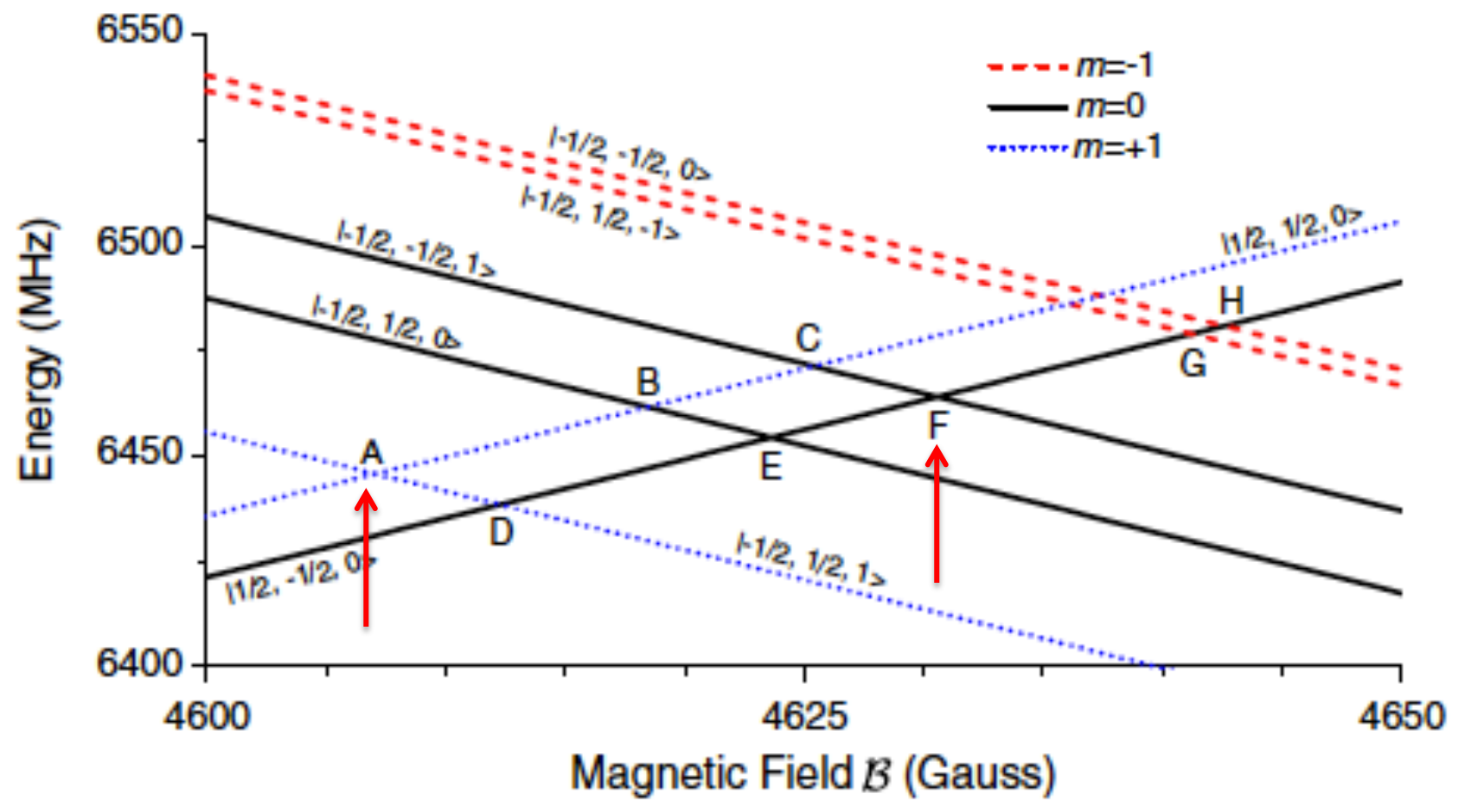


•Eliminates PMT bkgd due to laser scattering

First Molecular Species: BaF

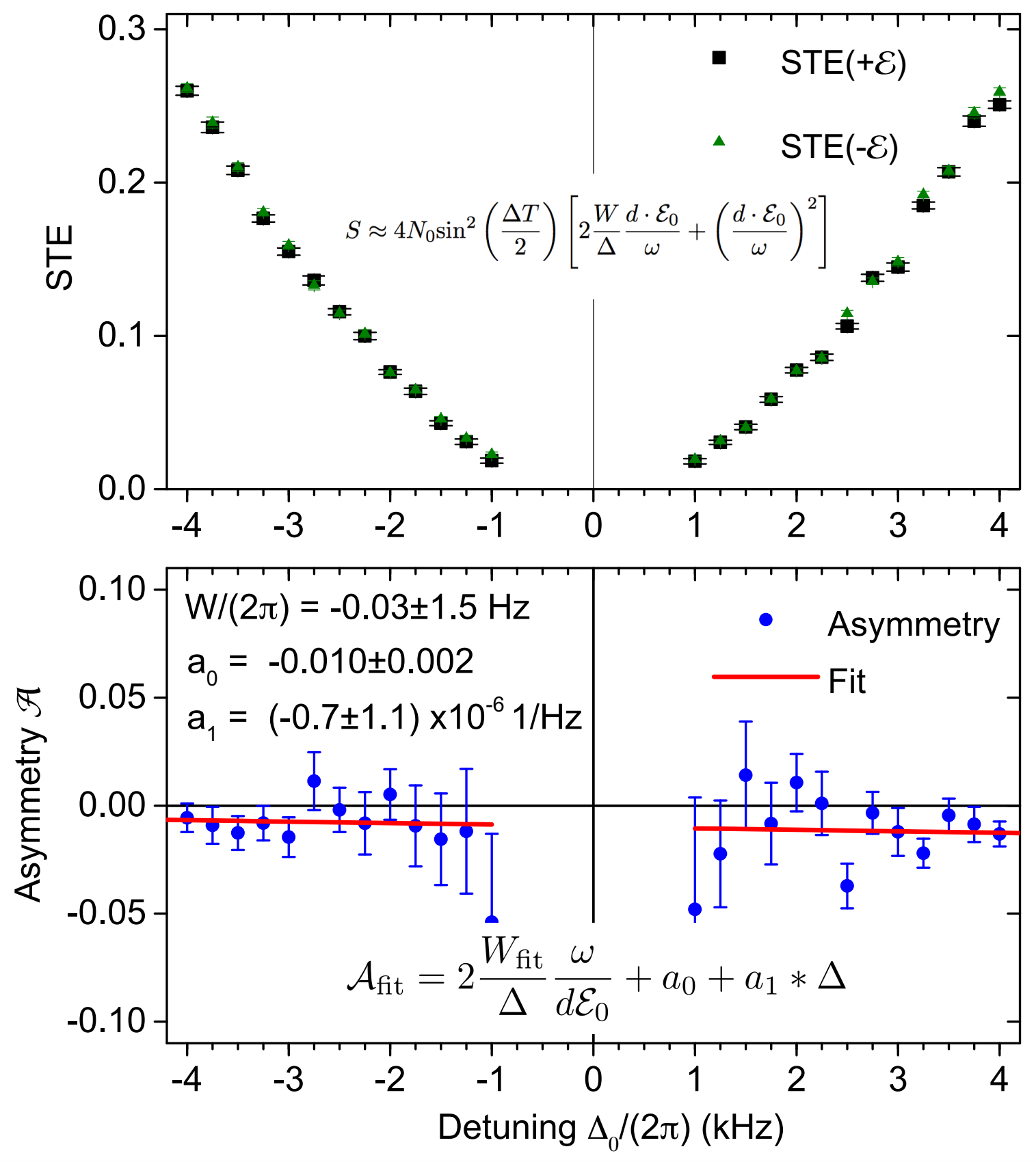
•NSD-PV measurement with ^{137}BaF

•Diagnostics with ^{138}BaF → no NSD-PV and larger signal



Ref. 2

Parity Violation Data with ^{138}BaF

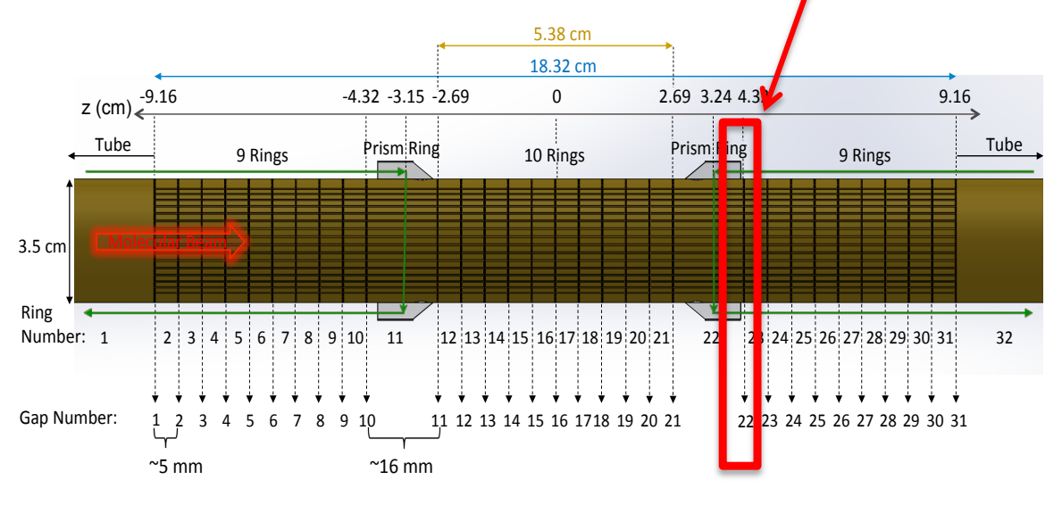


Ref. 4

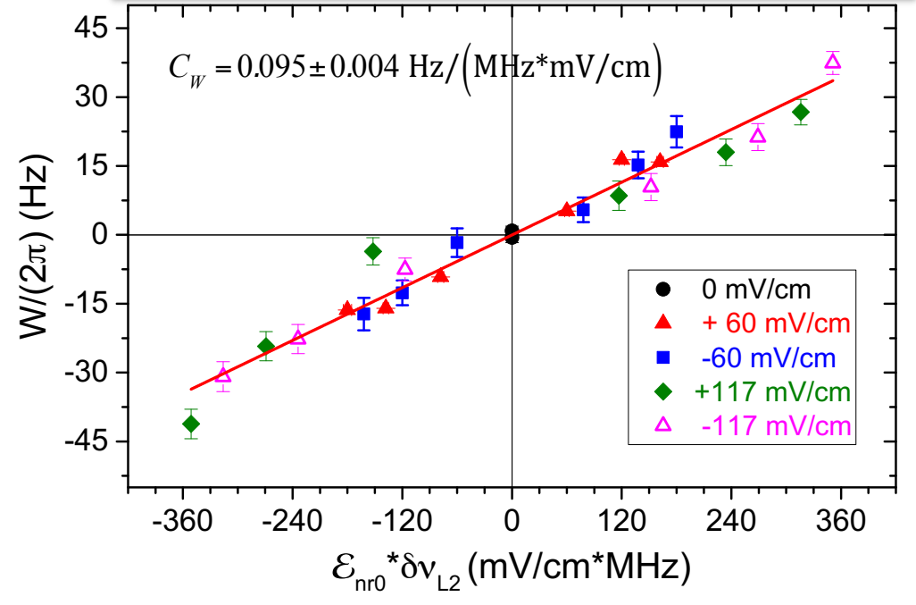
Systematic errors due to combinations of imperfections

- Non-reversing E field (E_{NR}) → detuning – even Asymmetry (e.g. vertical offset)
- E_{NR} + B gradients (B_{grad}) → detuning – odd Asymmetry → mimics parity violation!

Parameter	Shift	Systematic $\delta W_{\rm sys}$ (Hz)	Uncertainty
Bipolar $\mathcal{E}_{nr}$ Pulses		0.12	
Unipolar $\mathcal{E}_{nr}$ Pulses		0.16	
$\mathcal{B}$-Field Inhomogeneities		0.24	
$\delta\nu_{L2}$ and $\mathcal{E}_{nr}$ at and near Gap 22	-0.04	0.21	
Total Systematic	-0.04	0.38	



E_{NR} & AC Stark Systematic



Result Consistent with Zero in Control Isotope ^{138}BaF

Crossing	$W/(2\pi)$ (Hz)	C	d (Hz/(V/cm))	$W_{\rm mol} = \kappa' W_P/(2\pi)$ (Hz)
A	$0.28 \pm 0.49_{\rm stat} \pm 0.38_{\rm sys}$	-0.41	3360	$-0.68 \pm 1.20_{\rm stat} \pm 0.93_{\rm sys}$
F	$0.01 \pm 0.51_{\rm stat} \pm 0.38_{\rm sys}$	+0.39	3530	$0.03 \pm 1.30_{\rm stat} \pm 0.97_{\rm sys}$
Weighted Average	-	-	-	$-0.36 \pm 0.88_{\rm stat} \pm 0.95_{\rm sys}$

$W \propto W_P\left(\kappa'_Z + \kappa'_a\right)\left(\hat{n}\times\vec{S}\right)\cdot\vec{I}$ $C \equiv \left(\hat{n}\times\vec{S}\right)\cdot\vec{I}$ Ref. 4

$$W_{\rm mol.} = -0.36 \pm 1.29\,\text{Hz}$$

$$\boxed{\text{Expected } |W_{\rm mol.}| \text{ for } ^{137}\text{Ba} \approx 160 * 0.07 \approx 11\,\text{Hz}}$$

$$\boxed{\text{Equiv. sensitivity to } \kappa'\text{: } 7\times \text{ better than JILA Cs anapole measurement (Ref. 5)}}$$

Control Over E_{NR} +AC Stark Systematic

•Detuning offset and drift in Lp2: $\Delta\delta_{L2} = -0.3 \pm 1.3$ MHz using He-Ne laser reference[1]

•Better optical frequency stability required to suppress E_{NR} + AC Stark systematic

•Plan for future: Modulation Transfer Spectroscopy (MTS) signal provides reliable frequency reference with long term stability, e. g. free from Doppler background[2,3]

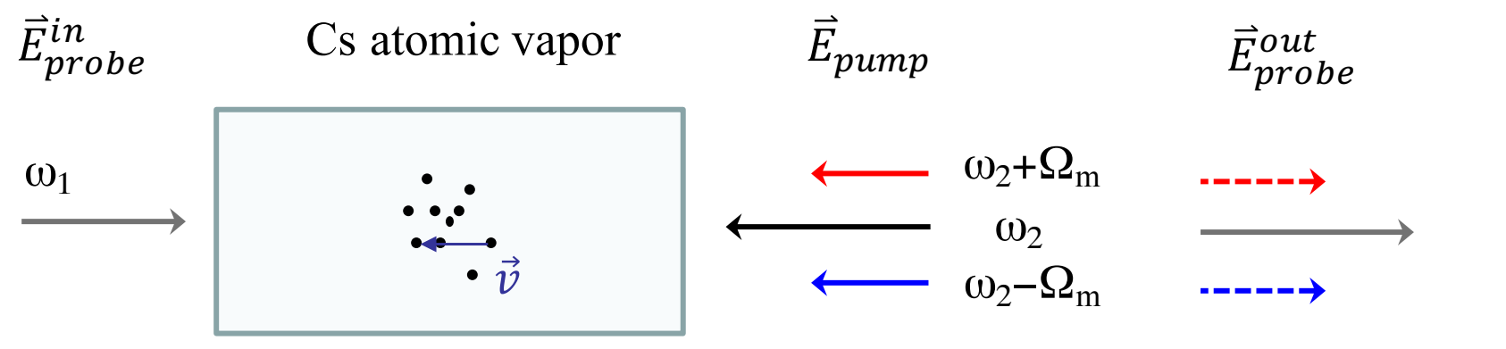
•Stable transfer cavity locked to frequency stabilized laser via PDH scheme[4] and molecule PV laser Lp2 offset-locked to transfer cavity

---

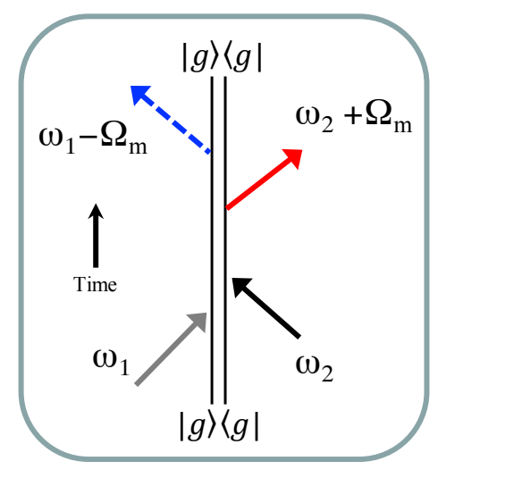
[1] Phys. Rev. Lett. **120**, 142501 (2018); Phys. Rev. A **97**, 042101 (2018)
[2] Opt. Lett. **7**, 537 (1982); Phys. Rev. A **25**, 2606 (1982);Meas. Sci. Technol. **19**, 105601 (2008)
[3] Chinese Phys. Lett. **26,** 044205 (2009); Appl. Opt. **56,** 2649 (2017)
[4] Appl. Phys. B: Photophys. Laser Chem. **31**, 97 (1983); Am. J. Phys. **69**, 79 (2001)

Frequency Reference: Modulation Transfer Spectroscopy

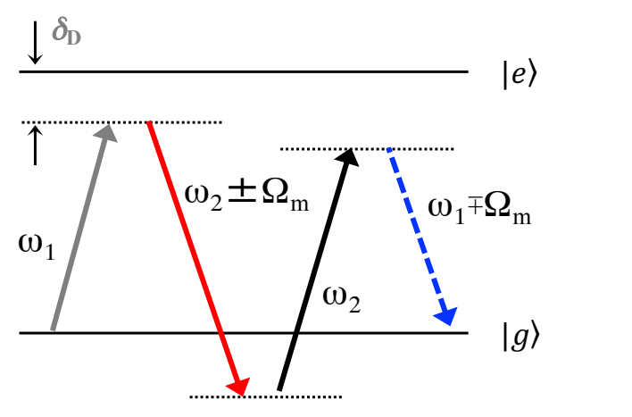
- Basic Concept of MTS



Interactions between probe and phase-modulated pump optical fields via atomic medium described by nonlinear four-wave mixing ($\chi^{(3)}$) process necessitating energy conservation and phase-matching.

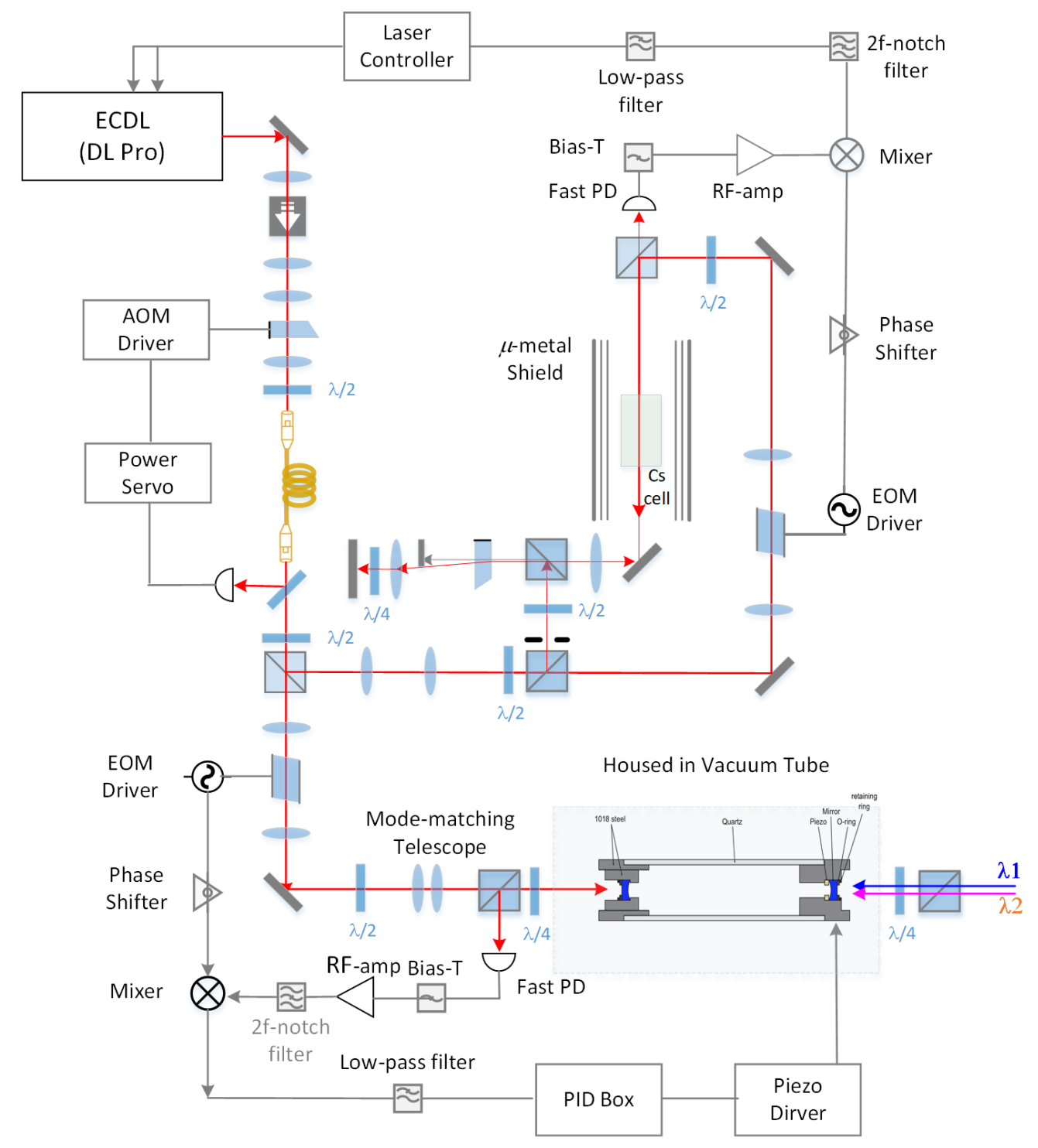


Double-sided Feynman diagram

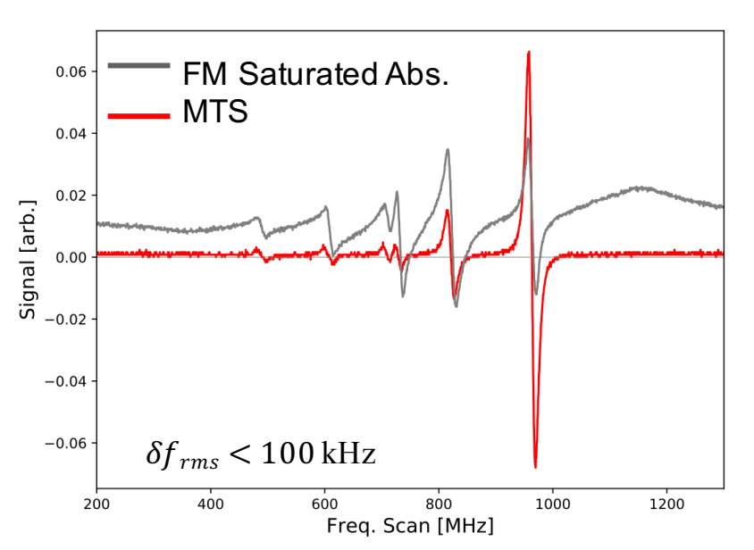


Energy level coupling diagram

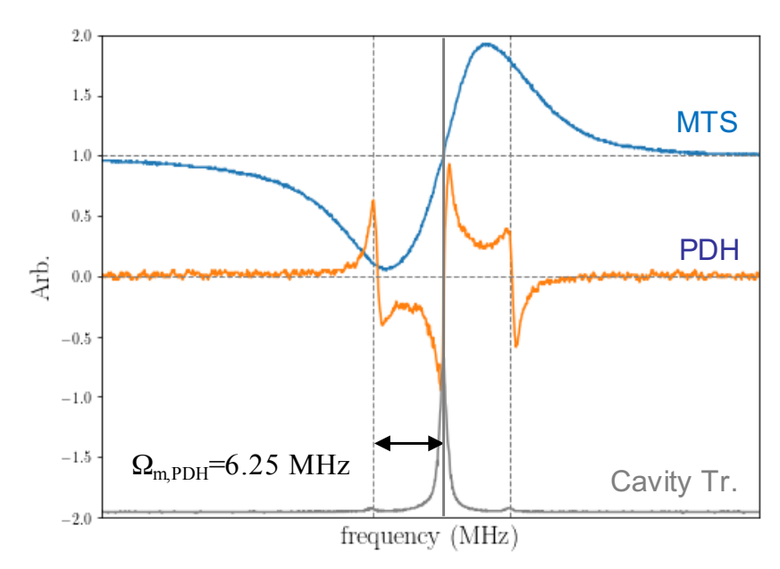
- Experimental Setup



Cs D2 Transitions (*F*=4 ↔ *F'* =3,4,5)



Transfer Cavity & PDH Lock



Summary and Outlook

•Short term goal→ measure NSD-PV in ^{137}BaF with 100x stronger and 3x slower buffer-gas source

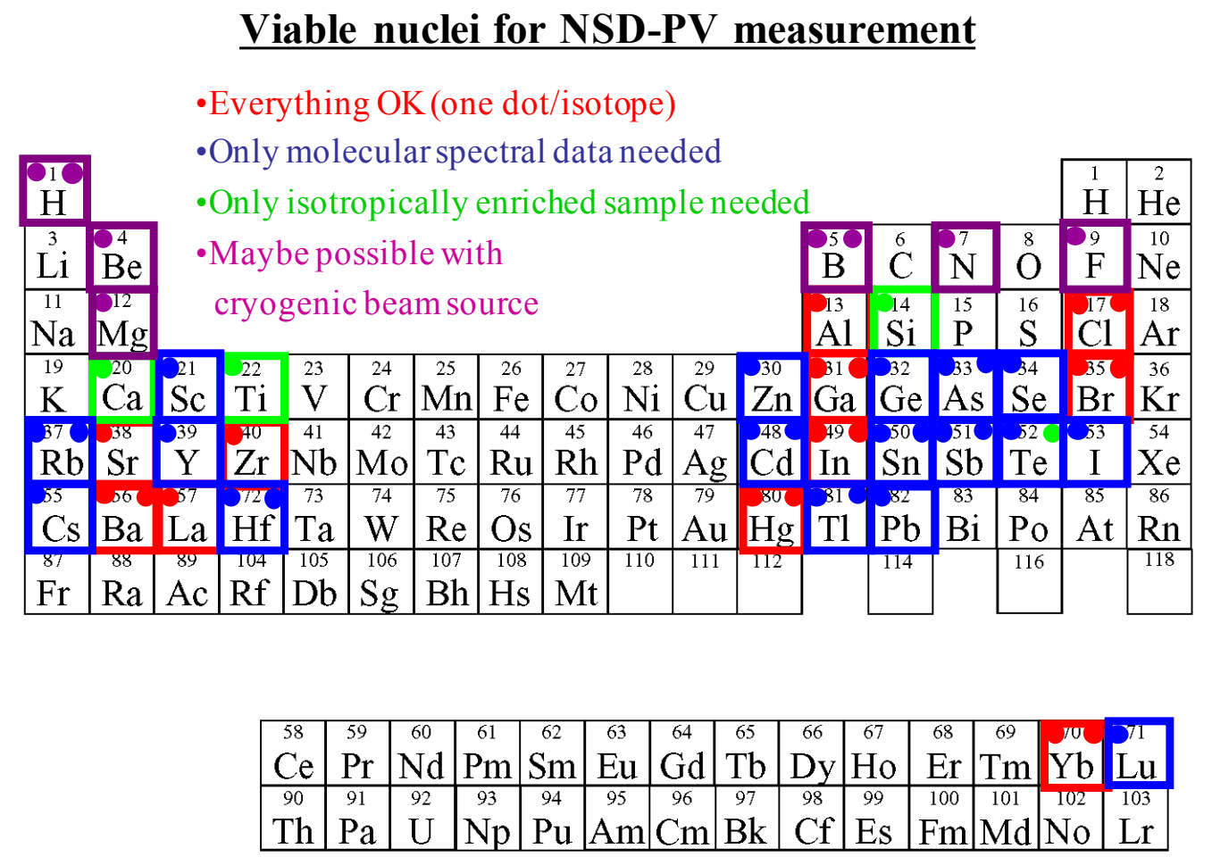
•Long term goal → measure NSD-PV in variety of nuclei

•NSD-PV effects scale differently with mass A and atomic number Z:
  – Anapole ∝ $A^{2/3}$
  –Z^0 exchange: constant w.r.to A
  –Overall signal ∝ Z^2

•To differentiate effects, must measure multiple nuclei, over wide mass range

Viable nuclei for NSD-PV measurement

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



For further information see

1) **D. DeMille *et al.*, Phys. Rev. Lett. 100, 023003 (2008)**
2) **S. B. Cahn *et al.*, Phys. Rev. Lett. 112, 163002 (2014)**
3) **E. Altuntas *et al.*, Phys. Rev. Lett. 120, 142501 (2018)**
4) **E. Altuntas *et al.*, Phys. Rev. A 97, 042101 (2018)**
5) **C. S. Wood *et al.*, Science 275, 1759 (1997)**