Atomic Parity Nonconservation Experiments at U.C. Berkeley

Dysprosium

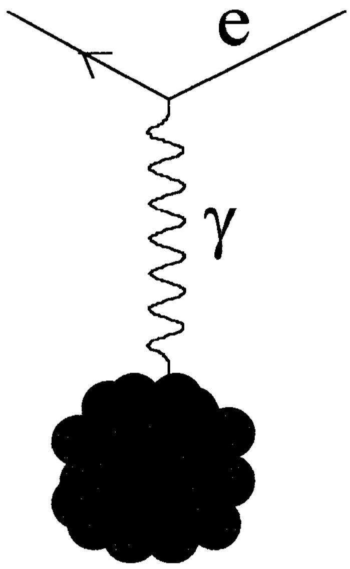
A.T. Nguyen
G.D. Chern
D. Budker
M. Zolotorev

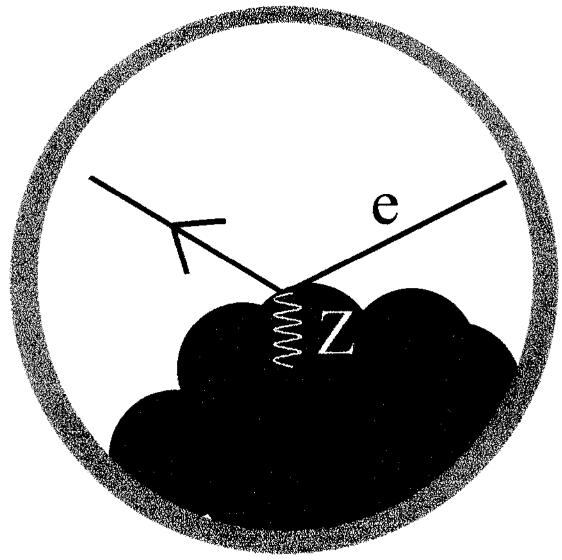
Ytterbium

J.E. Stalnaker
D. Budker
S.J. Freedman
G. Stoessel
V.V. Yashchuk
S. Anjum

http://socrates.berkeley.edu/~budker/

Weak Interaction in Atoms

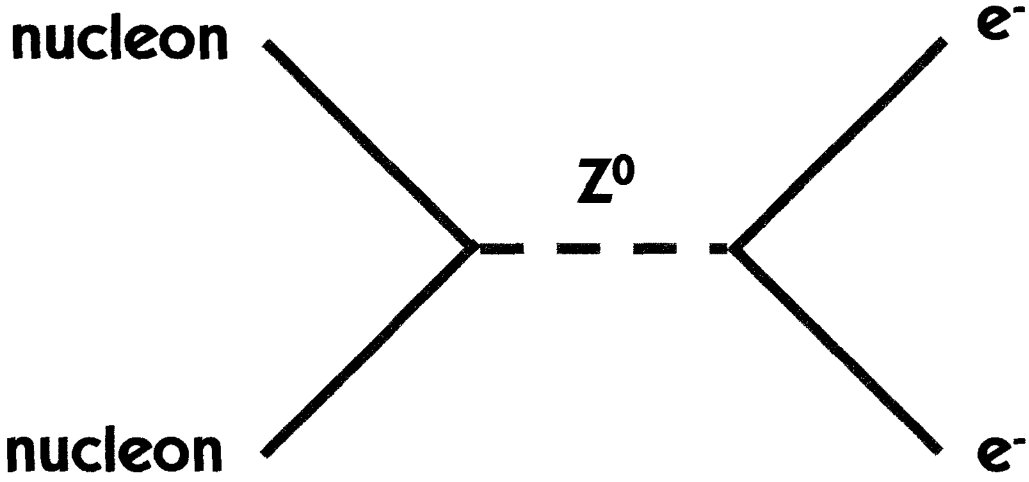




Electromagnetic interaction (conserves parity)	Weak interaction (violates parity)
$\Pi\Psi(\vec{r})=\pm\Psi(\vec{r})$	$\Pi\Psi(\vec{r})\neq\pm\Psi(\vec{r})$

PNC Mechanisms

Z^0 Exchange



- **Nuclear-Spin-Independent Coupling:**
  - **Grows as $\sim Z^3$**
- **Nuclear-Spin-Dependent Coupling:**
  - **Suppressed by $\sim (1 - 4\sin^2\theta_W)$**
  - **Grows as $\sim Z^2$**

Measurement of Weak Charge:

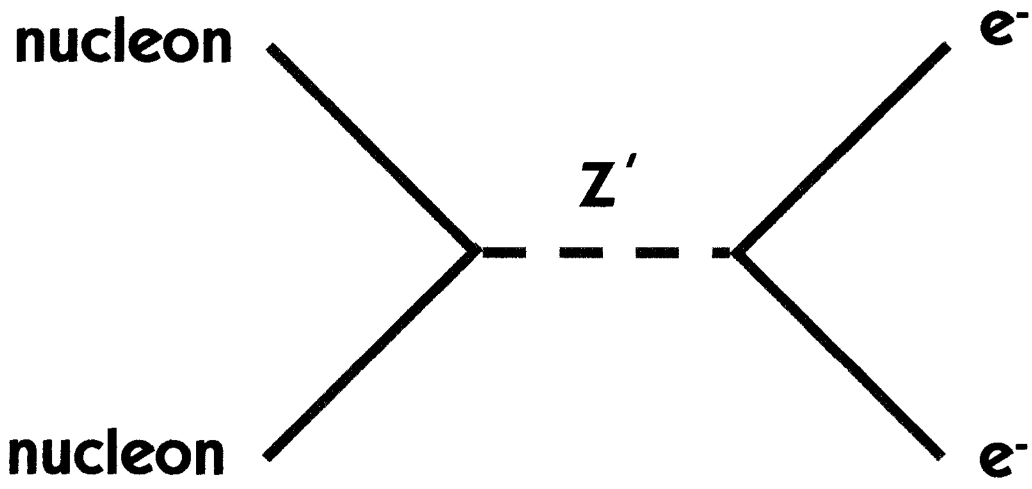
- $Q_W = \rho(-N + Z(1 - 4\sin^2\theta_W))$

Weak Mixing Angle: **$\sin^2\theta_W = 0.23124(24)$**

The ρ Parameter: $\rho \equiv \dfrac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1$

New Tree Level Physics

M.J. Ramsey-Musolf Phys. Rev. C 60, 015501



$$Q_W(N,Z) = Q_W^{SM} + Z\,\Delta Q_W^{P} + N\,\Delta Q_W^{N}$$

$$\frac{\Delta Q_W}{Q_W^{SM}} \approx \frac{8\sqrt{2}\,\pi\,\kappa^2}{\Lambda^2\, G_F}$$

Strongly interacting theories: $\kappa^2 \sim 1$

Weakly interacting theories: $\kappa^2 \sim \alpha$

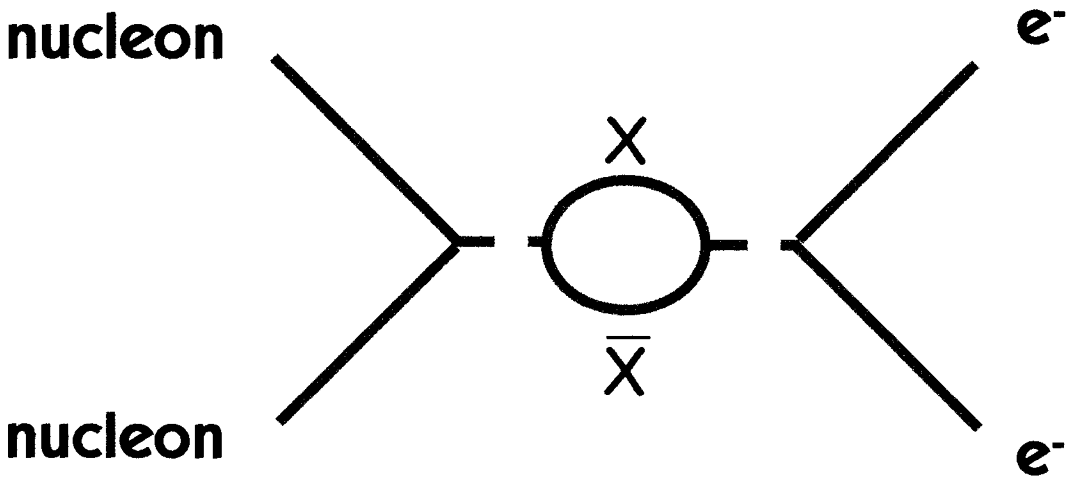
$$\frac{\delta Q_W}{Q_W^{SM}} \approx 1\%$$

$$\Downarrow$$

$$\Lambda \geq 20\,\kappa \text{ TeV}$$

Oblique Radiative Corrections

M.E. Peskin and T. Takeuchi, Phys. Rev. Lett. 65, 964 (1990).
W.J. Marciano and J.L. Rosner, Phys. Rev. Lett.. 65, 2963 (1990).



Isospin Conserving: S

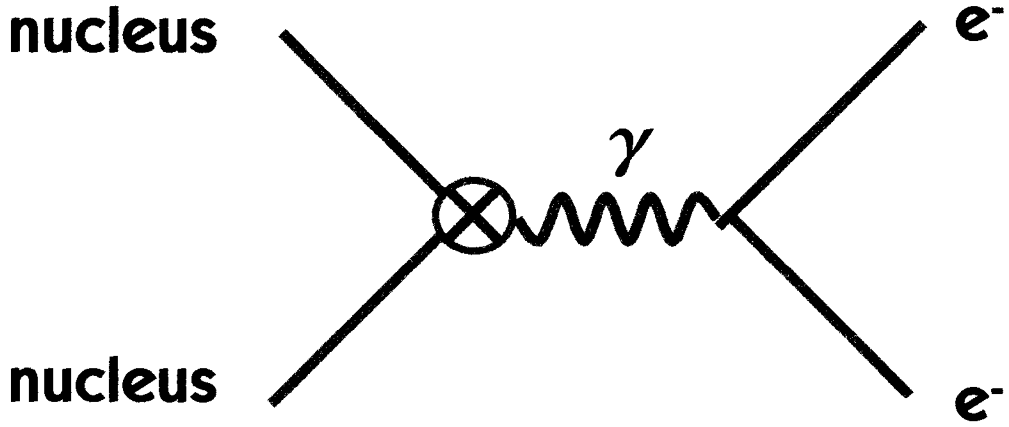
Isospin Breaking: T

$$\rho = 0.9857(1 + 0.0078\, T)$$

$$\sin^2\theta_W = 0.232 + 0.00365\, S - 0.00261\, T$$

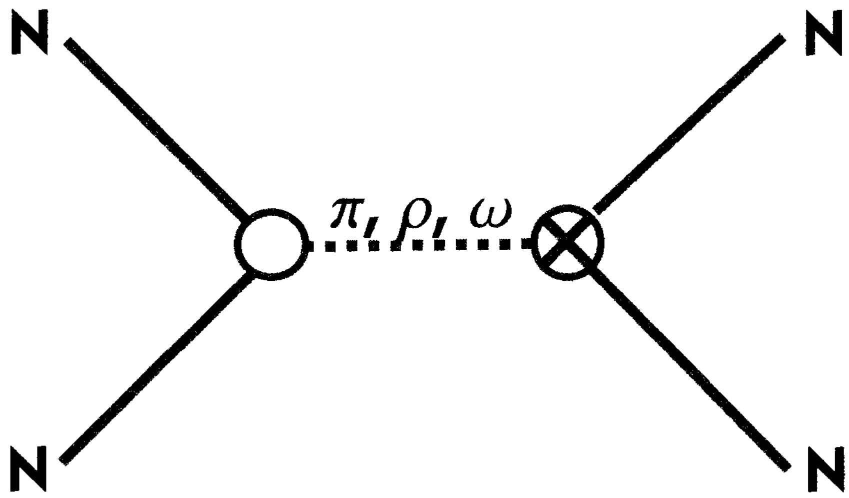
PNC Mechanisms

Nuclear Anapole Moment



- **Nuclear-Spin-Dependent Coupling:**
  - **Grows as** $\sim$ **$A^{2/3}$ Z^2**
  - **Suppressed by** α
- **Dominant Spin-Dependent Atomic PNC Effect for A $\gtrsim$ 20**

Nuclear Parity Violation



Possible Parity Violating Exchange Mesons

Light Mesons Dominate

No Neutral J=0 Meson Exchange
Between On-Shell Nucleons
(CP Invariance)

$\pi^{\pm}$	$\Delta \mathbf{I} = 1$
$\rho^{0,\pm}$	$\Delta \mathbf{I} = 0, 1, 2$
ω^{0}	$\Delta \mathbf{I} = 0, 1$

$\Rightarrow$ Six Coupling Constants

DDH Values

B. Desplanques, J.F. Donoghue, and B.R. Holstein, Ann. Phys. 124, 449 (1980).

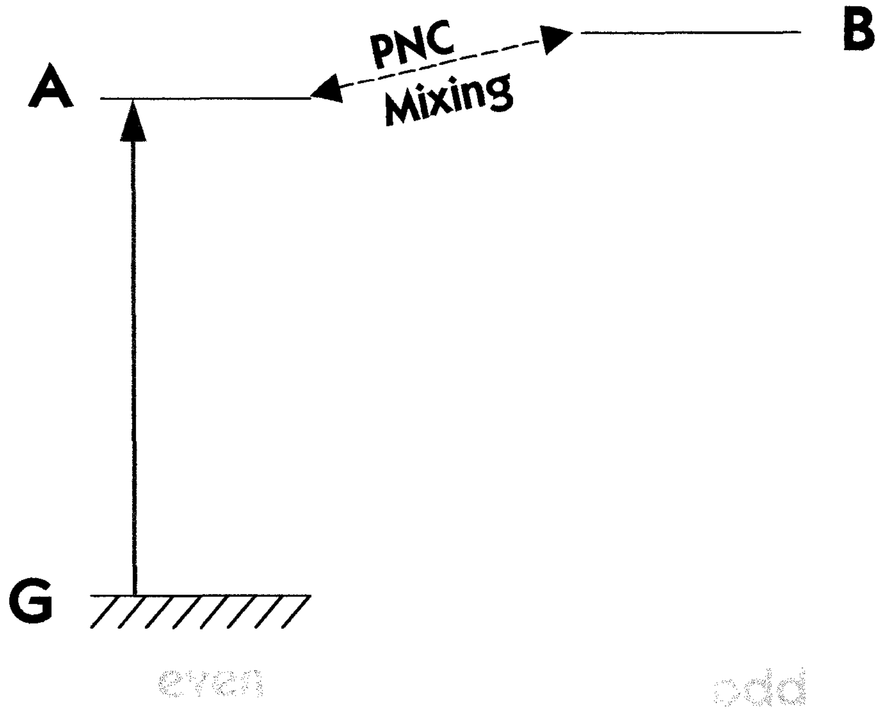
Calculated coupling constants using quark couplings with strong interaction dressings

Coupling	Best Value	Reasonable Range
f_π^1	4.6	$0 \rightarrow 11.4$
h_ρ^0	-11.6	$-31 \rightarrow 11.4$
h_ρ^1	-0.19	$-0.38 \rightarrow 0$
h_ρ^2	-9.5	$-11.0 \rightarrow -7.6$
h_ω^0	-1.9	$-10.3 \rightarrow 5.7$
h_ω^1	-1.1	$-1.9 \rightarrow -0.8$

Values of Coupling Constants
$\Rightarrow$ Strong Interaction at Low q^2

PNC Atomic Transitions

Energy eigenstates are not eigenstates of parity



$$|\tilde{A}\rangle = |A\rangle + \frac{\langle B|H_W|A\rangle}{E_A - E_B}|B\rangle$$

⇒Electric dipole transition between two states with same nominal parity

Typically, $A_{PNC} \approx 10^{-10}\ e\ a_0$

PNC Experiments

Interfere A_{PNC} with a larger PARTIY-CONSERVING amplitude

$$R = |A_{PC} + A_{PNC}|^2$$

$$R = A_{PC}^2 + A_{PC} A_{PNC}$$

$A_{PC} = M1$

OPTICAL ROTATION:

Tl: P.A. Vetter, *et al.*, Phys. Rev. Lett. 74, 2658 (1995).

Pb: D.M. Meekhof, *et al.*, Phys. Rev. Lett. 71, 3442 (1993).

Bi: M.J.D. McPherson, *et al.*, Phys. Rev. Lett. 67, 2784 (1991).

$A_{PC} = E1_{Stark}$

STARK INTERFERENCE:

Cs: C.S. Wood, *et al.*, Science, 275, 1759 (1997).

M.C. Noecker, B.P. Masterson, and C.E. Wieman, Phys. Rev. Lett. 61, 310 (1988).

Nuclear-Spin-Independent PNC

Single Isotope Measurements

Measure: $A_{PNC} = \zeta\, Q_W$

Calculate: ζ

Test: $Q_W = \rho[-N + Z(1 - 4\sin^2\theta_W)]$

Weak Mixing Angle: $\sin^2\theta_W = 0.23124(24)$

The ρ Parameter: $\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1$

Isotope Ratio

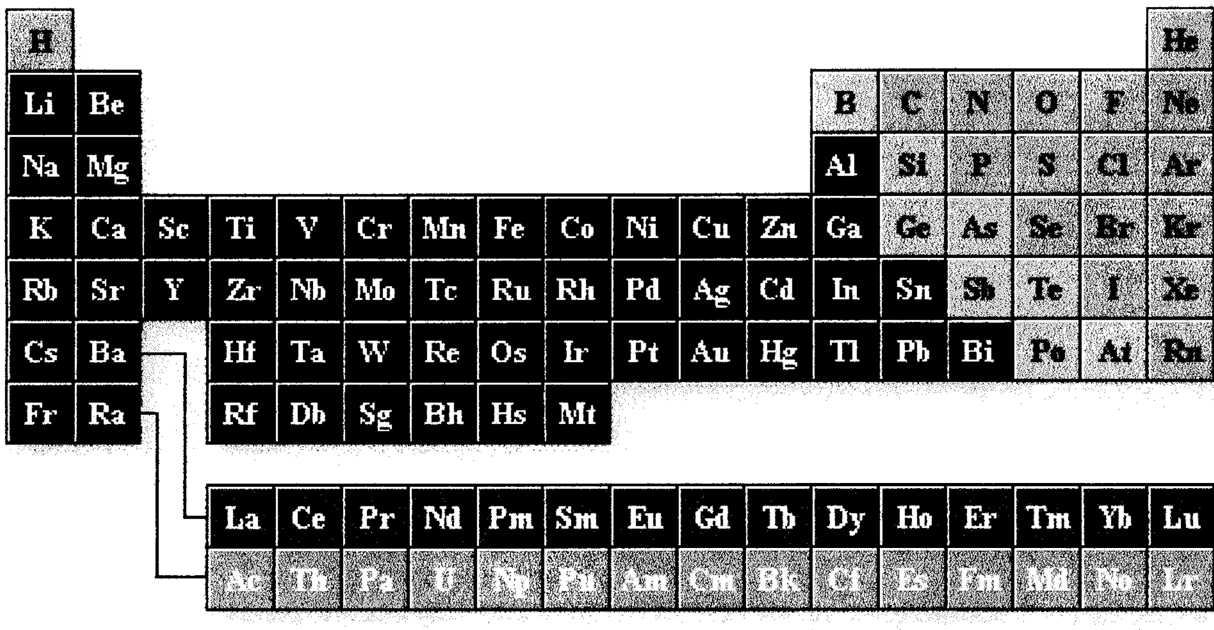
Measure: $\begin{cases} A_{PNC}(N) = \zeta\, Q_W(N) \\ \& \\ A_{PNC}(N') = \zeta\, Q_W(N') \end{cases}$

Ratio Doesn't Depend on ζ

$$R = \frac{A_{PNC}(N)}{A_{PNC}(N')} = \frac{Q_W(N)}{Q_W(N')}$$

But ... Loss in sensitivity: $\dfrac{N}{\Delta N}$

PNC in Rare-Earth Atoms



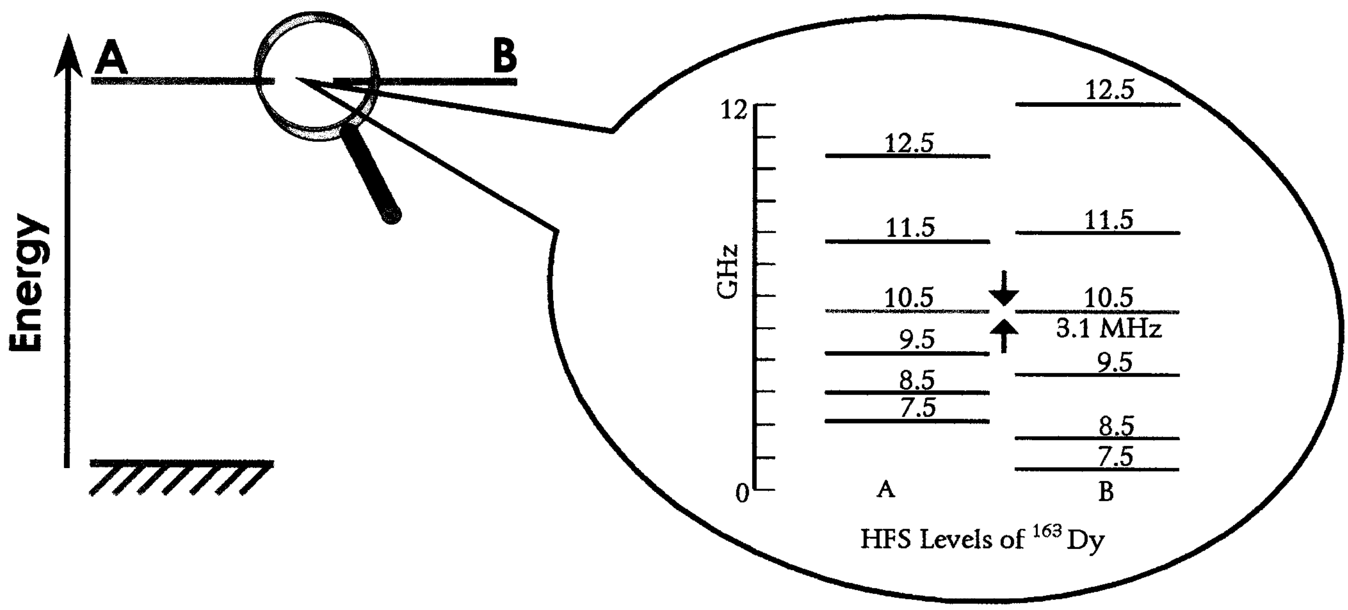
- **Heavy atoms**
  - **PNC effect grows as Z^3**
- **Close-lying energy levels of opposite parity**
  - **Possible enhancement of PNC effects**

$$\left|\Psi_{even}\right\rangle' = \left|\Psi_{even}\right\rangle + \sum_{odd} \frac{\left\langle\Psi_{odd}\middle|H_w\middle|\Psi_{even}\right\rangle}{E_{even} - E_{odd}} \left|\Psi_{odd}\right\rangle$$

- **Many Stable Isotopes**
  - **Isotopic Comparison**

Dysprosium

Extraordinarily small ΔE between opposite parity levels A & B in dysprosium: ΔE ~ hyperfine structure & isotope shifts



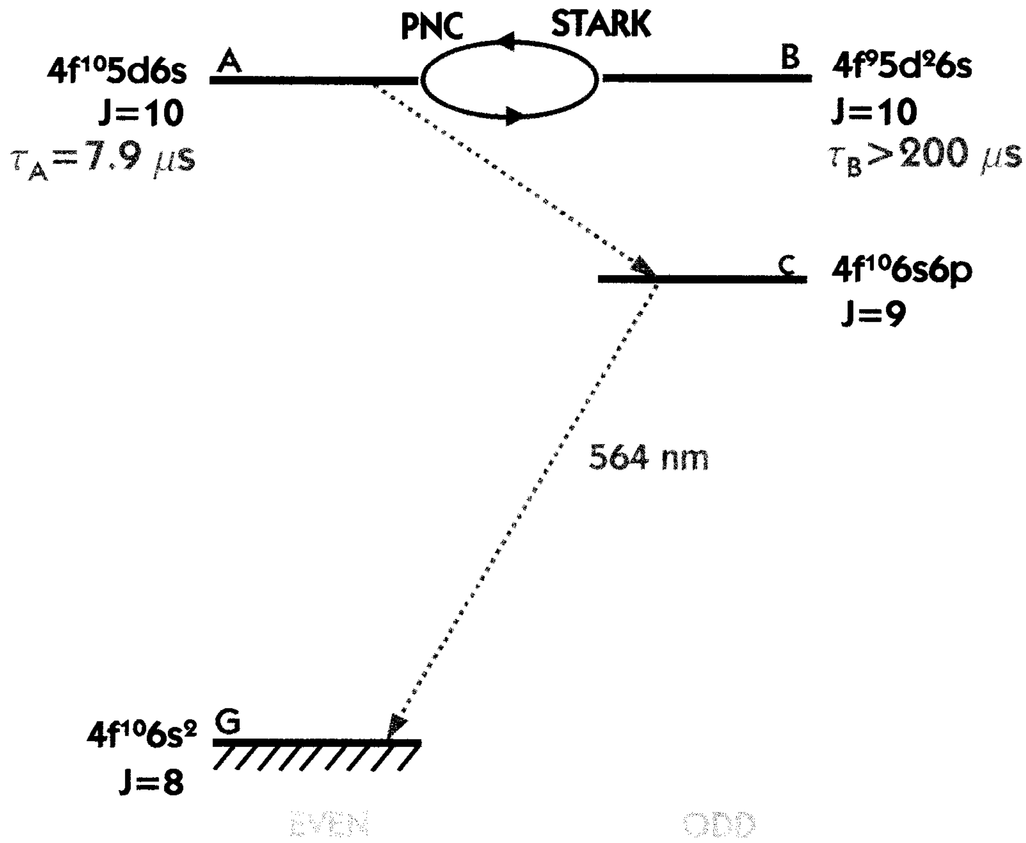
ΔE can be further decreased by applying a small external B-field

Unfortunately, dominant configurations don't mix

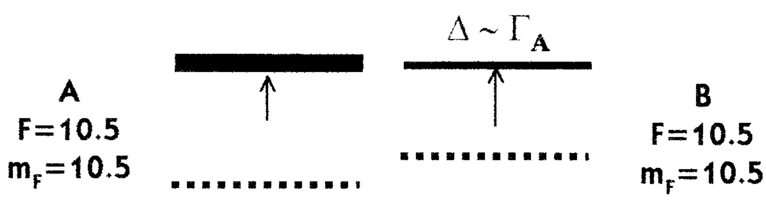
Theory : $H_W = 70 \pm 40$ Hz

Dzuba *et al.*, PRA 50, 3812

Dy Energy Levels



Apply B-field to bring sublevels of A & B to near-crossing.



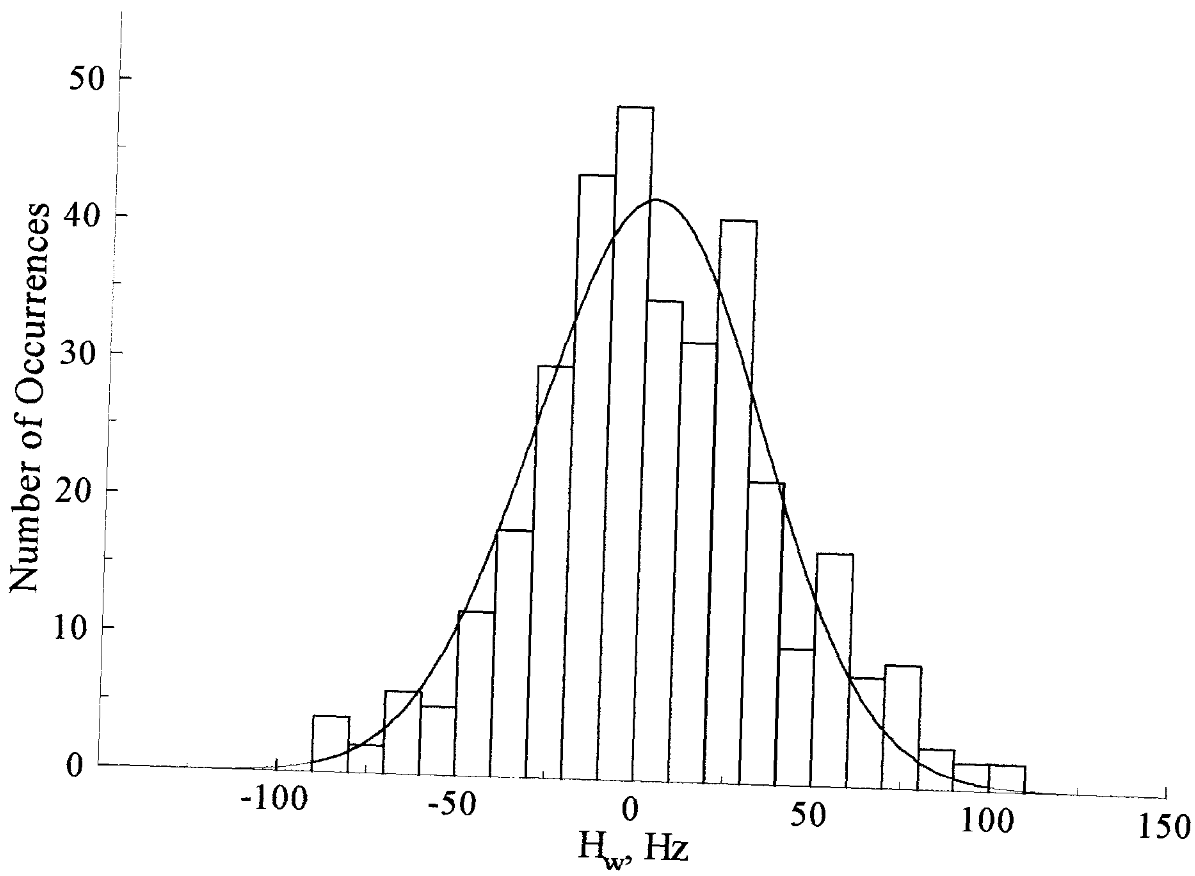
Apply time varying E-field to Stark mix sublevels.

Look for PNC-Stark interference by observing temporal dynamics of fluorescence.

Dy Results

Final Value:

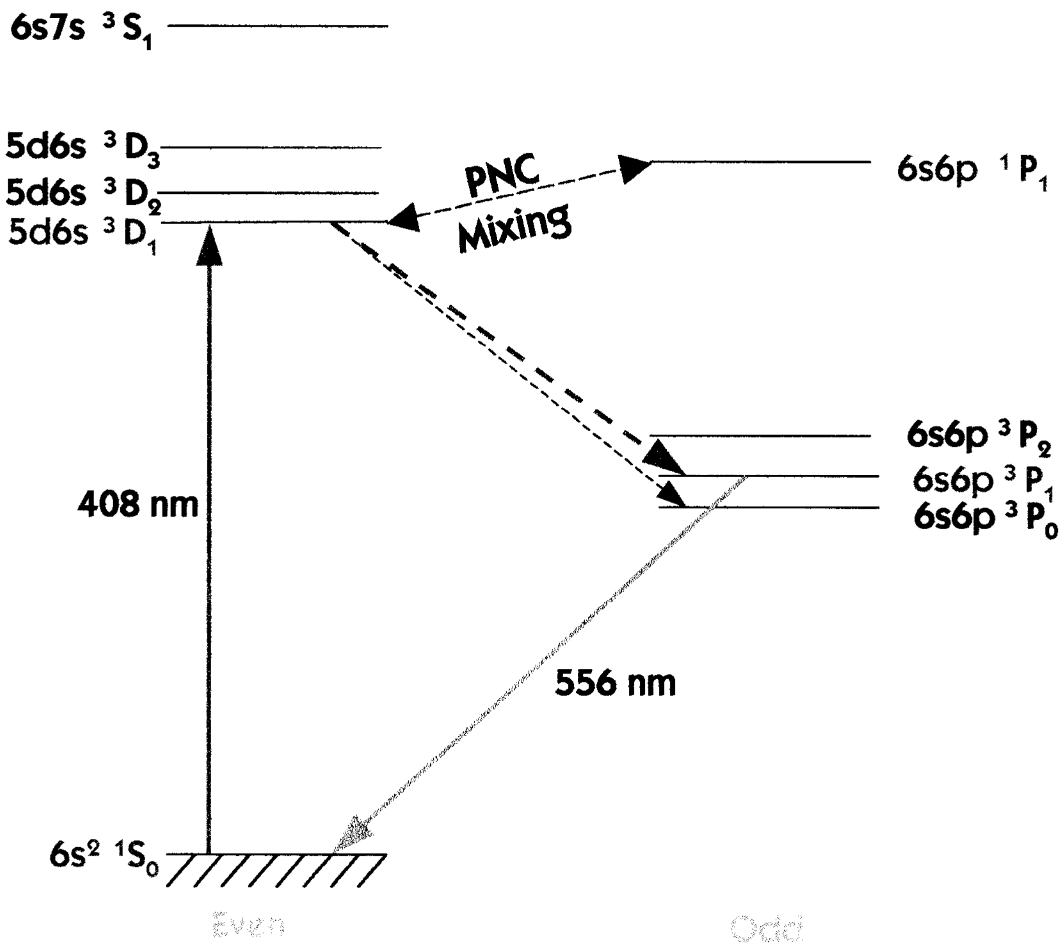
$H_w = |2.3 \pm 2.9 \text{ (statistical)} \pm .7 \text{ (systematic)}|$ Hz



Statistics Limited ⇒ Improve Counting Rate

Ytterbium

D.DeMille, PRL 74, 4165 (1995)



$^3D_1$ and $^1P_1$ state separated by 589 cm^{-1}
$^1P_1$ state has ≈15% 5d6p

➤ $E1_{PNC} = i\ 1.15(25) \times 10^{-9}\ ea_0\ (Q_W/N)$

Porsev *et. al.*, Pis'ma Zh.Éksp. Teor. Fiz. 61, 449 (1995)
B.P. Das, Phys. Rev. A 56, 1635 (1997)

Seven Stable Isotopes ΔN=8

Suppressed M1 amplitude

➤ PNC-Stark interference

Stark-Interference

External E-field produces Stark-induced amplitude

$$E1_{Stark} = i\beta(\vec{\epsilon} \times \vec{E})_M$$

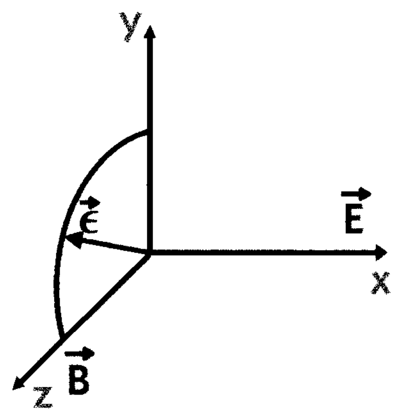
Interfere $E1_{PNC}$ and $E1_{Stark}$ transition amplitudes

$$R = |E1_{Stark} + E1_{PNC}|^2$$

$$= |\beta E + E1_{PNC}|^2$$

$$\approx \beta^2 E^2 + 2\beta E\, E1_{PNC}$$

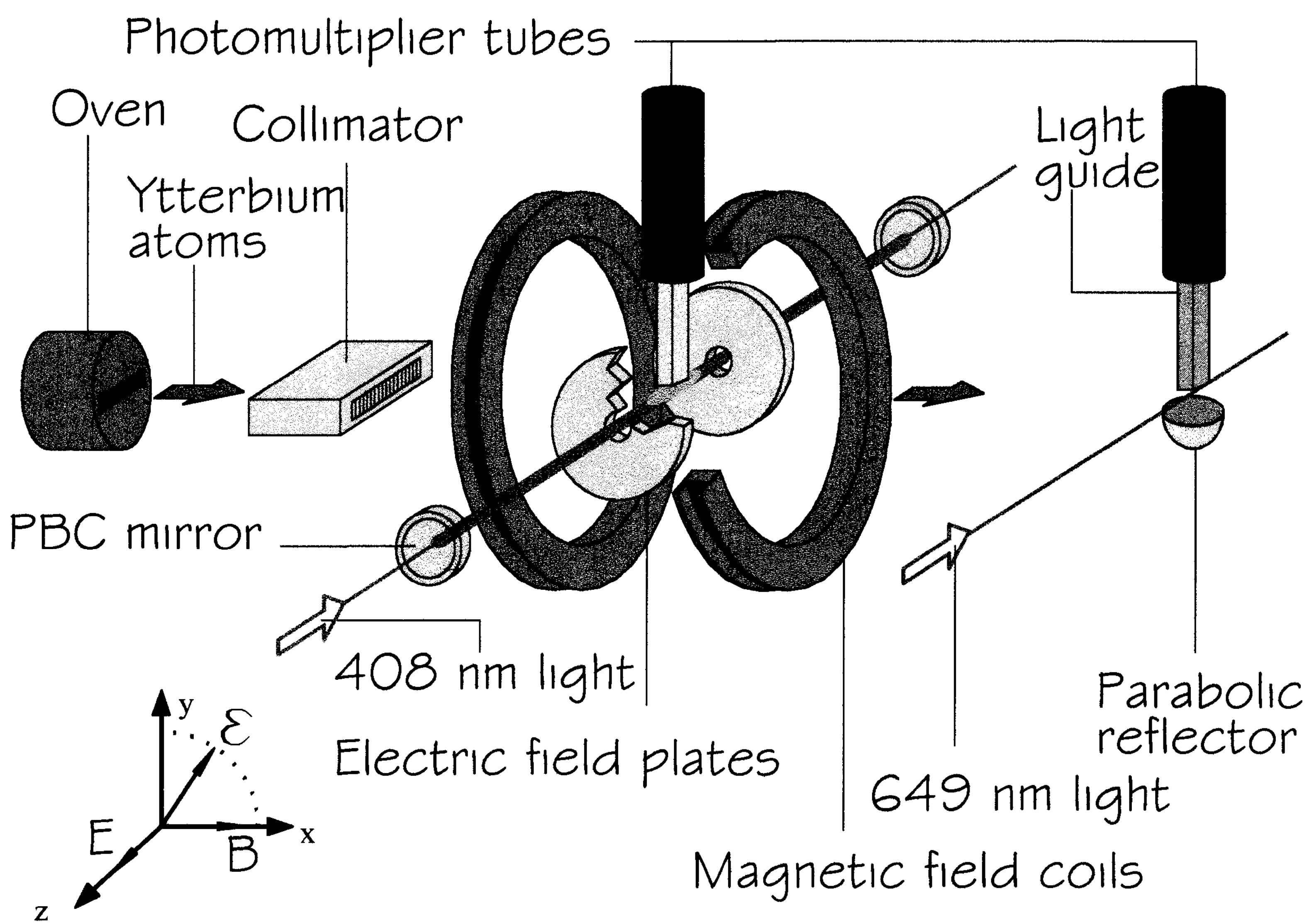
Possible Geometry for PNC-Stark interference



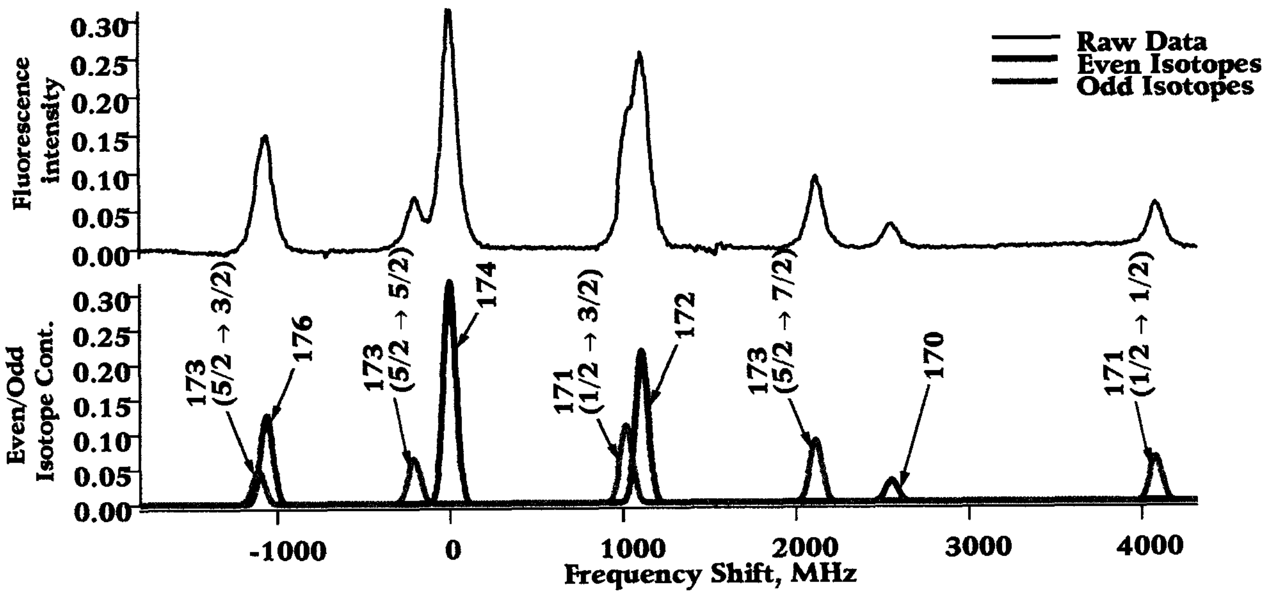
Interference term proportional to

$$\left(\vec{\epsilon} \cdot \vec{B}\right)\left(\left(\vec{\epsilon} \times \vec{E}\right) \cdot \vec{B}\right)$$

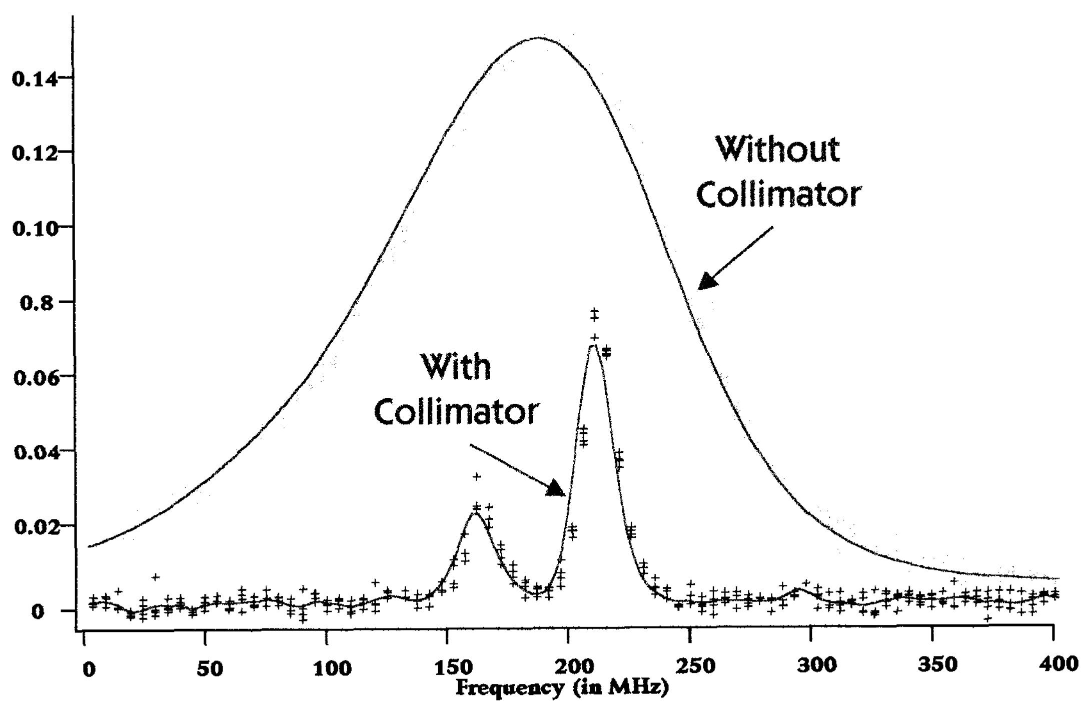
PNC Experiment



Excitation Spectrum



408 excitation spectrum of natural abundance of Yb in the presence of a dc electric field (~45 kV/cm)



^{176}Yb and ^{173}Yb F=5/2 → F=3/2

M1 Measurement

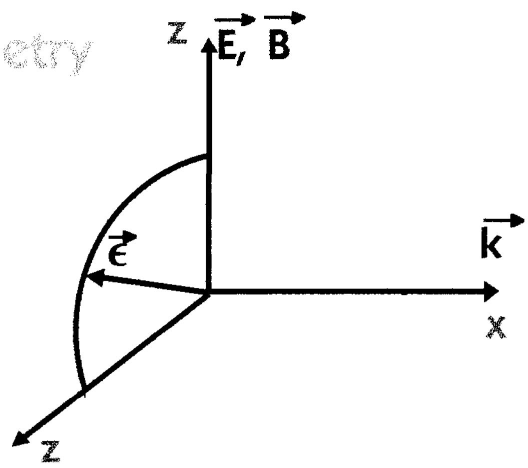
M1 amplitude highly suppressed ...
but still much bigger than $E1_{PNC}$

- **Measure M1 to understand effect on PNC experiment**

Estimated Size: $M1 \leq 10^{-4}\ \mu_B$
(DeMille;1995)

Use Stark-M1 interference

Geometry



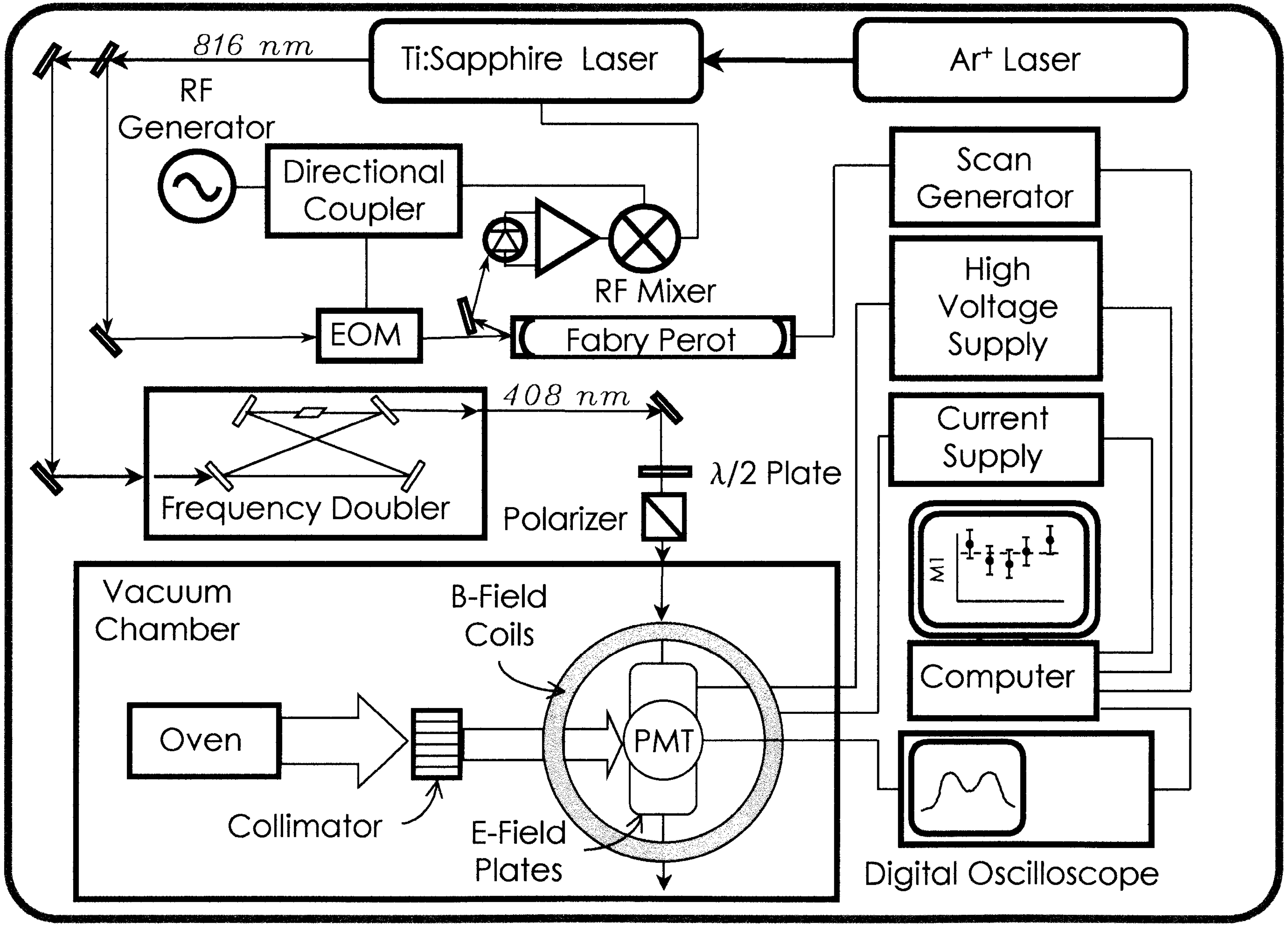
Interference term is proportional to:

$$\left(\vec{\epsilon}\times\vec{E}\right)\times\left(\vec{\epsilon}\times\vec{k}\right)\cdot\hat{B}$$

M1-Stark Interference Signatures

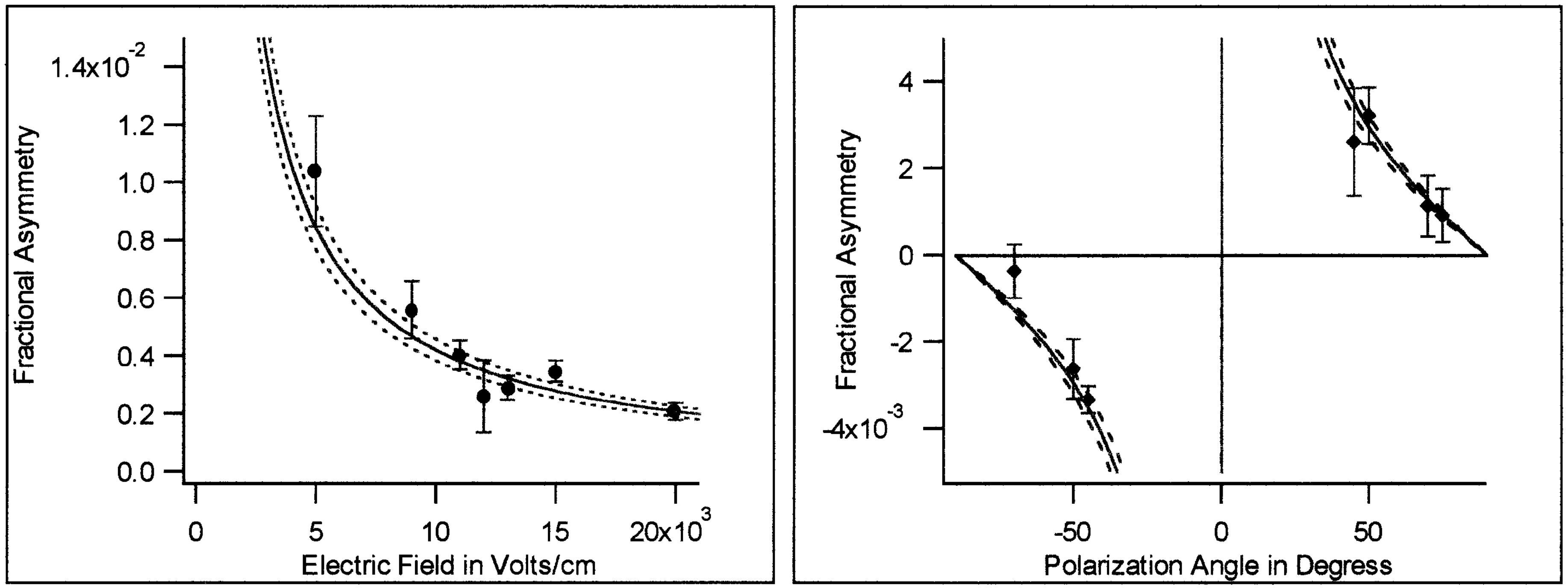
- **Odd with Electric Field**
- **Odd with Magnetic Field**
- **Odd with Magnetic Sublevel**
- **Odd with Polarization Angle**

Block Diagram for M1 Experiment



M1 Results

$$\langle 6s^2\ {}^1S_0 | M1 | 5d6s\ {}^3D_1, M_J = \pm 1 \rangle = 1.26(11)_{stat}(19)_{sys} \times 10^{-4}\,\mu_B$$



Fractional asymmetry for different experimental configurations

Progress Towards PNC

Completed Work

- Lifetime Measurements
- General Spectroscopy (hyperfine, isotope shifts)
- Stark Shift Measurements
- Stark-Induced Amplitude Measurement
- M1 Measurement

Near future

- Add power build-up cavity
  - ⇒ Characterize ac Stark shifts
- PNC in string of isotopes
- Anapole moment

Conclusions

- Atomic PNC is a unique system for studying neutral weak currents

- Anapole moment provides window into strong interactions at low q^2

- Dysprosium and Ytterbium are promising systems for:
  - Isotopic comparison of nuclear-spin-dependent PNC effects
  - Anapole moment measurements