Prospects for Atomic Parity Violation Experiments

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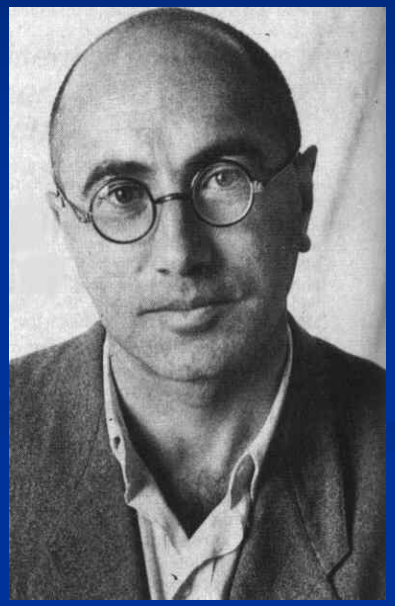
Outline

- A brief story of parity violation in atoms
- Mechanisms of APV
- Summary of measurements of atomic parity violation
- Prospects for new experiments on APV
- Berkeley experiment with Yb isotopes: present status and perspectives

Atomic PNC: important landmarks

- ✓ 1959 **Ya. B. Zel'dovich:** PNC (Neutr. Current) ⇒ Opt. Rotation in atoms
- ✓ 1974 **M.-A. & C. Bouchiat** Z^3 enhancement ⇒ PNC observable in **heavy** atoms
- ✓ 1978-9 **Novosibirsk, Berkeley** discovery of PNC in OR(Bi) and Stark-interf.(Tl)
- ✓ 1995 **Boulder, Oxford, Seattle, Paris** PNC measured to 1-2% in Cs, Tl, Bi, Pb
- ✓ 1997 **Boulder** 0.35% measurement, discovery of anapole moment

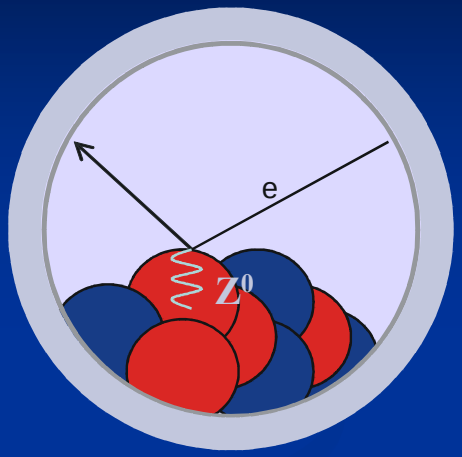


Prof. Ya. B. Zel'dovich

Sources of parity violation in atoms

Z^0-exchange between e and nucleus

$\Rightarrow$ P-violating, T-conserving product of axial and vector currents



$$\hat{h} = -\frac{G}{\sqrt{2}} \sum_N \left[C_{1N} \bar{e}\gamma_\mu\gamma_5 e \, \bar{N}\gamma_\mu N + C_{2N} \bar{e}\gamma_\mu e \, \bar{N}\gamma_\mu\gamma_5 N \right]$$

C_{1n} is by a factor of 10 larger than C_{1p}, C_{2N} leading to a dominance of the time-like nuclear spin-independent interaction (A_e,V_N)

A contribution to APV due to Z^0 exchange between electrons is suppressed by a factor ~1000 for heavy atoms.

Nuclear Spin-Independent (NSI) electron-nucleon interaction

NSI Hamiltonian in non-relativistic limit assuming equal proton and neutron densities $\rho(r)$ in the nucleus:

$$\hat{h}_W = -\frac{G}{2\sqrt{2}} Q_W \gamma_5 \rho(r)$$

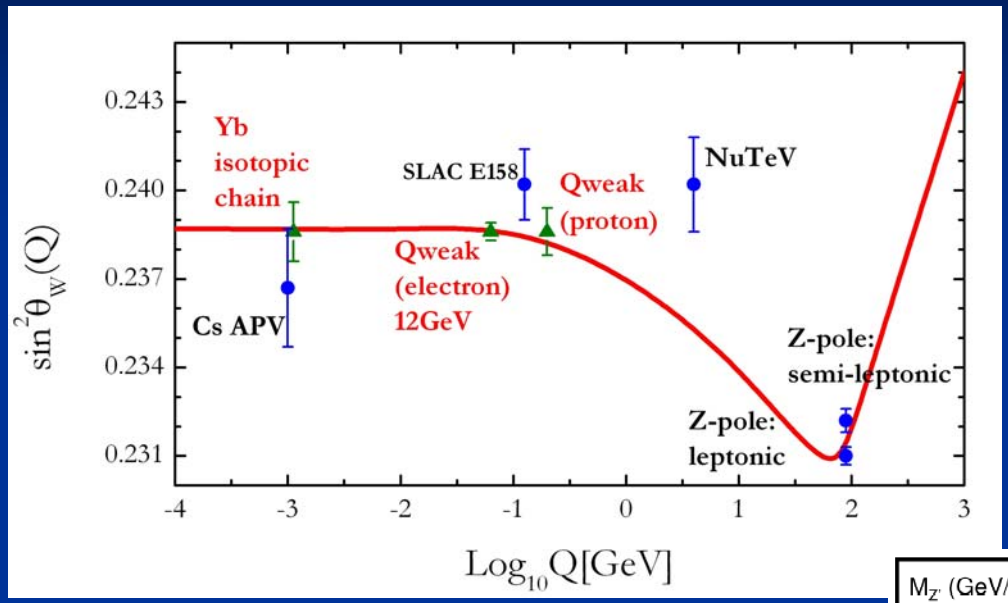
The nuclear weak charge Q_W to lowest order in the electroweak interaction is

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

The nuclear weak charge is protected from strong-interaction effects by conservation of the nuclear vector current. **Thus, APV measurements allows for extracting weak couplings of the quarks and for searching for a new physics beyond SM**

- NSI interaction gives the largest PNC effect compared to other mechanisms
- NSI interaction is scalar $\Rightarrow$ mixes only electron states of same angular momentum **j**

NSI interaction and particle physics implications

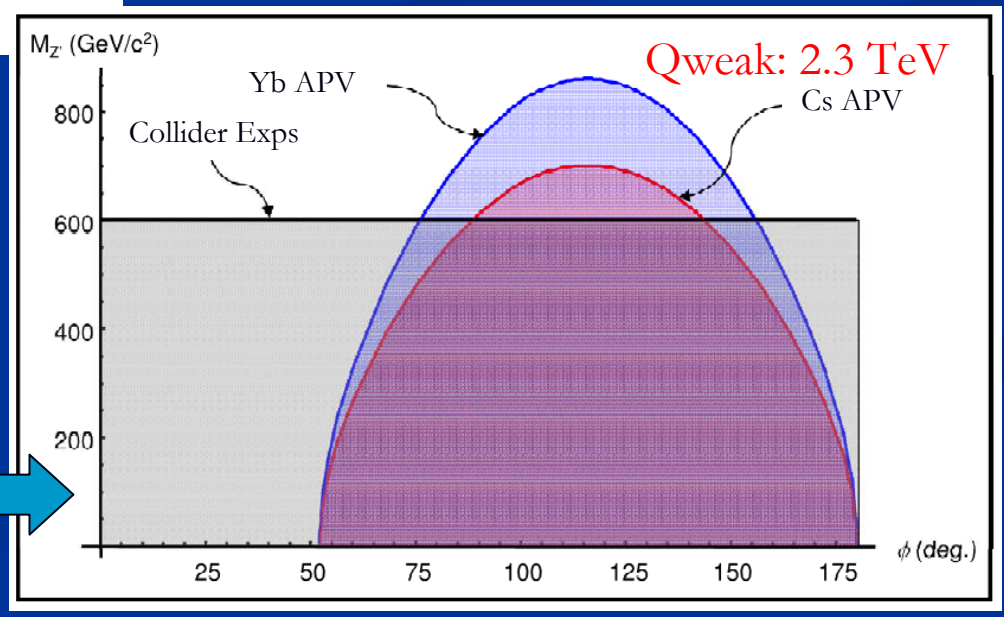


APV utilizes low-energy system and gives an access to the weak mixing angle, $\mathrm{Sin}^2(\theta_W)$, at low-momentum transfer.

- J.L. Rosner, PRD 1999
- V.A. Dzuba, V.V. Flambaum, and O.P. Sushkov, PRA 1997
- J. Erler and P. Langacker, Ph.Lett. B 1999

APV experiments are sensitive to new tree-level physics at energies that cannot be currently achieved in colliders.

Limits of the mass and mixing angle for Z' in E_6 models. The shaded area is excluded by the measurements of APV and from collider experiments

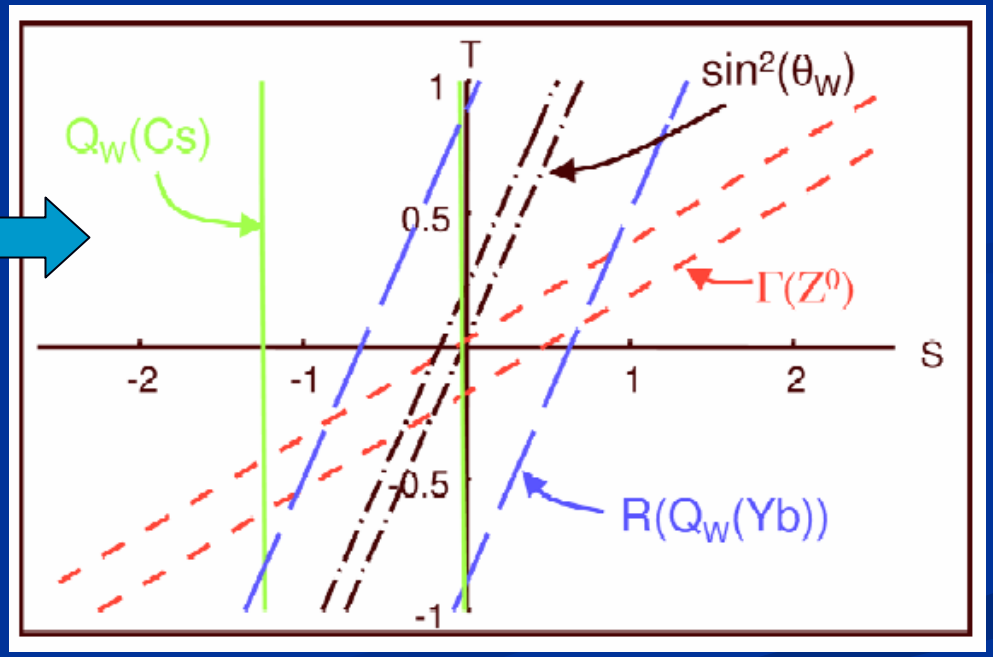


NSI interaction and particle physics implications (continued)

Standard Model extensions, Oblique radiative corrections, Higgs sector.

Precision measurements of electroweak quantities constrain linear combinations of **S** – isospin conserving, and **T** – isospin breaking parameters.

Constraints of S and T from $\Gamma(Z^0)$ and from value of $\mathrm{Sin}^2(\theta_W)$ as determined from forward-backward scattering asymmetries



M.J. Ramsey-Musolf, PRC 1999

APV experiments are not providing complimentary information to the high-energy experiments

Thus, the impact of the NSI APV is expected in constraining new tree-level physics rather than oblique radiative corrections

Isotope ratios and neutron distribution

The atomic theory errors can be excluded by taking ratios of APV measurements along an isotopic chain. While the atomic structure cancels in the isotope ratios, there is an enhanced sensitivity to the neutron distribution $\rho_n(r)$.

$$A_{PNC} = \delta(Q_W + Q_W^{nuc})$$

$$Q_W^{nuc} = -N(q_n - 1) + Z(1 - 4\sin^2\theta_W)(q_p - 1)$$

$$q_n = \int \rho_n(r) f(r) \mathrm{d}^3 r, \;\; q_p = \int \rho_p(r) f(r) \mathrm{d}^3 r$$

f(r) is the variation of the electron wave functions inside the nucleus normalized to f(0)=1.

$$R \equiv \frac{A_{PNC}(N')}{A_{PNC}(N)} \approx \frac{Q_W(N')}{Q_W(N)}\left[1 + \Delta q_n\right]$$

$$\Delta q_n \equiv q_n - q_n'$$

R is sensitive, in particular, to the difference in the neutron distributions.

This could be used to determine nuclear structure and test nuclear models complementing parity violating electron scattering measurements

~Z^3 scaling of APV effects

Considering the electron wave functions in **nonrelativistic** limit and **point-like** nucleus the NSI Hamiltonian becomes:

$$\hat{h}_W = \frac{G}{4\sqrt{2}m_e}\left(\sigma\cdot\mathrm{p}\ \delta^3(\mathrm{r}) + \delta^3(\mathrm{r})\ \sigma\cdot\mathrm{p}\right)$$

Since it is a local and a scalar operator it mixes only **s** and $\mathbf{p_{1/2}}$ states.

$$\left\langle p_{1/2}\left|\hat{h}_W\right|s\right\rangle \propto Z^2 Q_W$$

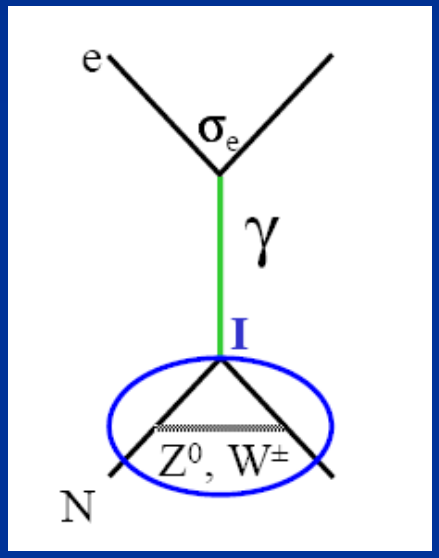
- Z due to scaling of the probability of the valence electron to be at the nucleus
- Z from the operator **p,** which near the nucleus (unscreened by electrons) ∝ Z.
- $|Q_W| \approx N \sim Z$.

Strong enhancement of the APV effects in heavy atoms

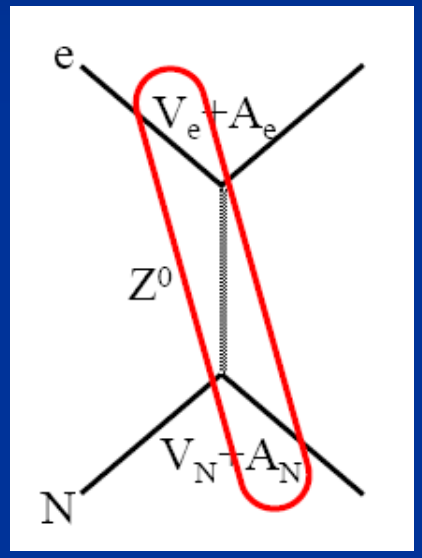
Sources of NSD interaction

$$\hat{h}_{NSD} = \frac{G}{\sqrt{2}} \frac{\kappa}{I} \gamma_0 \boldsymbol{\gamma}\mathbf{I}\ \rho(\vec{r})$$

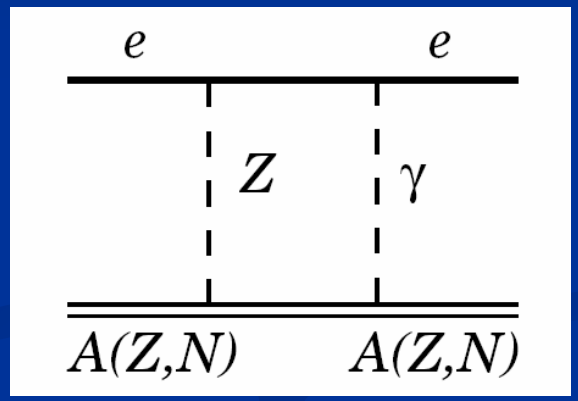
Anapole moment



Weak neutral current



Hyperfine correction to the weak neutral current



$$\kappa = \frac{\mathrm{K}}{I+1}\kappa_A + \kappa_2 + \kappa_{Q_w};$$

$$\mathrm{K} = (-1)^{I+1/2-l}(I+1/2)$$

$$\kappa_A \approx 1.15 \cdot 10^{-3} A^{2/3} \mu_\alpha g_\alpha; \quad A = N + Z;$$

$$\kappa_2 = \frac{1/2 - \mathrm{K}}{I+1} C_{2\alpha}$$

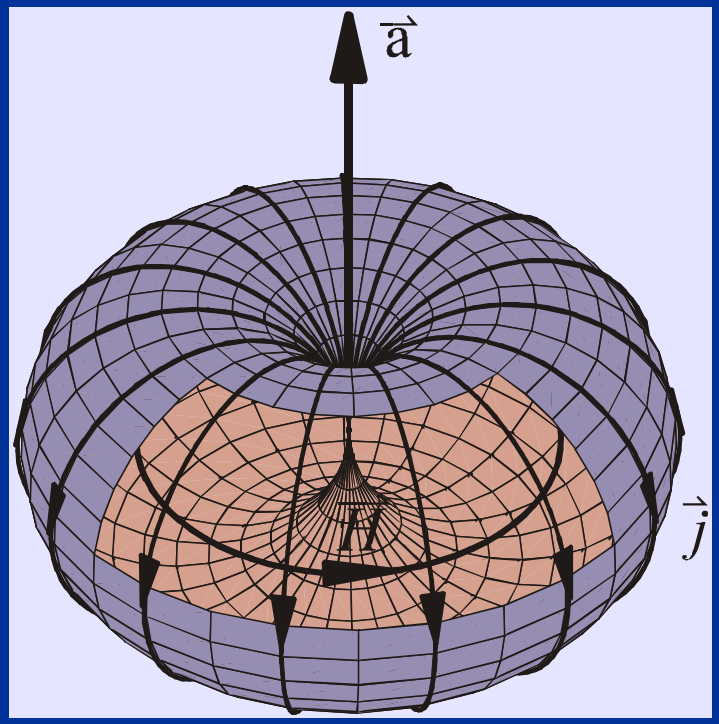
κ_A-Anapole moment
κ_2-Neutral currents
κ_{QW}-Radiative corrections

Anapole moment

In the nonrelativistic approximation PNC interaction of the valence nucleon with the nuclear core has the form:

$$\hat{h}_A \sim \frac{G\, g_\alpha}{2\sqrt{2}} \frac{(\boldsymbol{\sigma}\mathbf{p})}{m_p} n(\vec{r})$$

n(r) is core density and g_α is dimensionless effective weak coupling constant for valence nucleon.



- As a result, the spin σ acquires projection on the momentum **p** and forms **spin helix**
- Spin helix leads to the toroidal current. This current is proportional to the magnetic moment of the nucleon and to the cross section of the core.

Khriplovich & Flambaum

$$\kappa_A \approx 1.15 \cdot 10^{-3} A^{2/3} \mu_\alpha g_\alpha$$

<u>**neutron**</u>: μ_n=-1.2; g_n=-1
<u>**proton**</u>: μ_p=3.8; g_p=5

Anapole moment is bigger for nuclei with unpaired <u>proton</u>

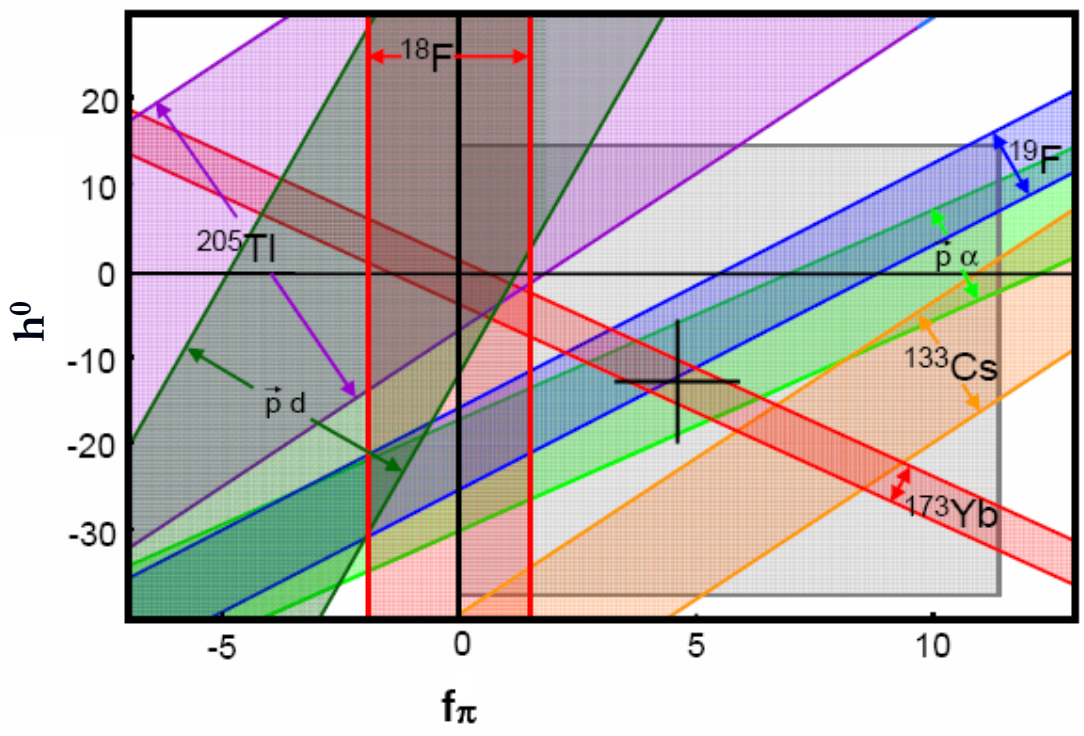
Nuclear physics implication: weak meson coupling constants

There are 7 independent weak couplings for π-, ρ-, and ω-mesons known as DDH constants. Proton and neutron couplings, g_α, can be expressed in terms of 2 combinations of these constants:

$$g_p = 8.0\times10^4\left[70f_\pi - 19.5h^0\right]$$
$$g_n = 8.0\times10^4\left[-47f_\pi - 18.9h^0\right]$$

$$f_\pi \equiv f_\pi^1 - 0.12h_\rho^1 - 0.18h_\omega^1$$
$$h^0 \equiv h_\rho^0 + 0.7h_\omega^0$$

At present the values of the coupling constants are far from being reliably established. The projected measurement of the anapole moment in ^{173}Yb should provide an important constraint.



Ask E158 SLAC group for an update after Jan. 2007

Signature of the weak interaction in atoms

$\mathbf{h_{NSI}}$ mixes $\mathbf{s_{1/2}}$ and $\mathbf{p_{1/2}}$ states of valence electron $\Rightarrow$
$\mathbf{A_{PV}}$ of dipole-forbidden transition.
If $\mathbf{A_{PC}}$ is also induced, the amplitudes interfere.

$$R \propto \left|A_{PC} + A_{PV}\right|^2 \cong A_{PC}^2 + 2A_{PC}A_{PV} + o(A_{PV}^2)$$

A'_{PC}

Interference

$\boldsymbol{A_{PC}A'_{PC}}$ interference

E-field → Stark-effect → E1 PC-amplitude ∝ E → E1-PNC interference term is odd in E

MUST:
Determine $\boldsymbol{A_{PC}}$ with high precision
Limit $\boldsymbol{A'_{PC}}$

ransition rate
$_V\mathbf{A_{Stark}}$

Results of APV measurements

Atom	Transition	Group	Year	Measurement	
				$-\mathrm{Im}(A_{PV}/M1)$ (10^{-8})	$-\mathrm{Im}(A_{PV}/\beta)$ (mV/cm)
^{209}Bi	$^4S_{3/2}$-$^2D_{3/2}$	Oxford	1991	10.12(20) **2%**	
^{208}Pb	$^3P_0$-$^3P_1$	Seattle	1993	9.86(12) **1.2%**	
		Oxford	1996	9.80(33) **3%**	
^{205}Tl	$6P_{1/2}$-$6P_{3/2}$	Oxford	1995	15.68(45) **3%**	
		Seattle	1995	14.68(17) **1.2%**	
^{133}Cs	$6S_{1/2}$-$7S_{1/2}$	Boulder	1988		1.576(34) **2%**
		Boulder	1997		1.558(6) **0.35%**
		Paris	2004		1.538(40) **2%**

* Measurements of APV with precision better than 5%

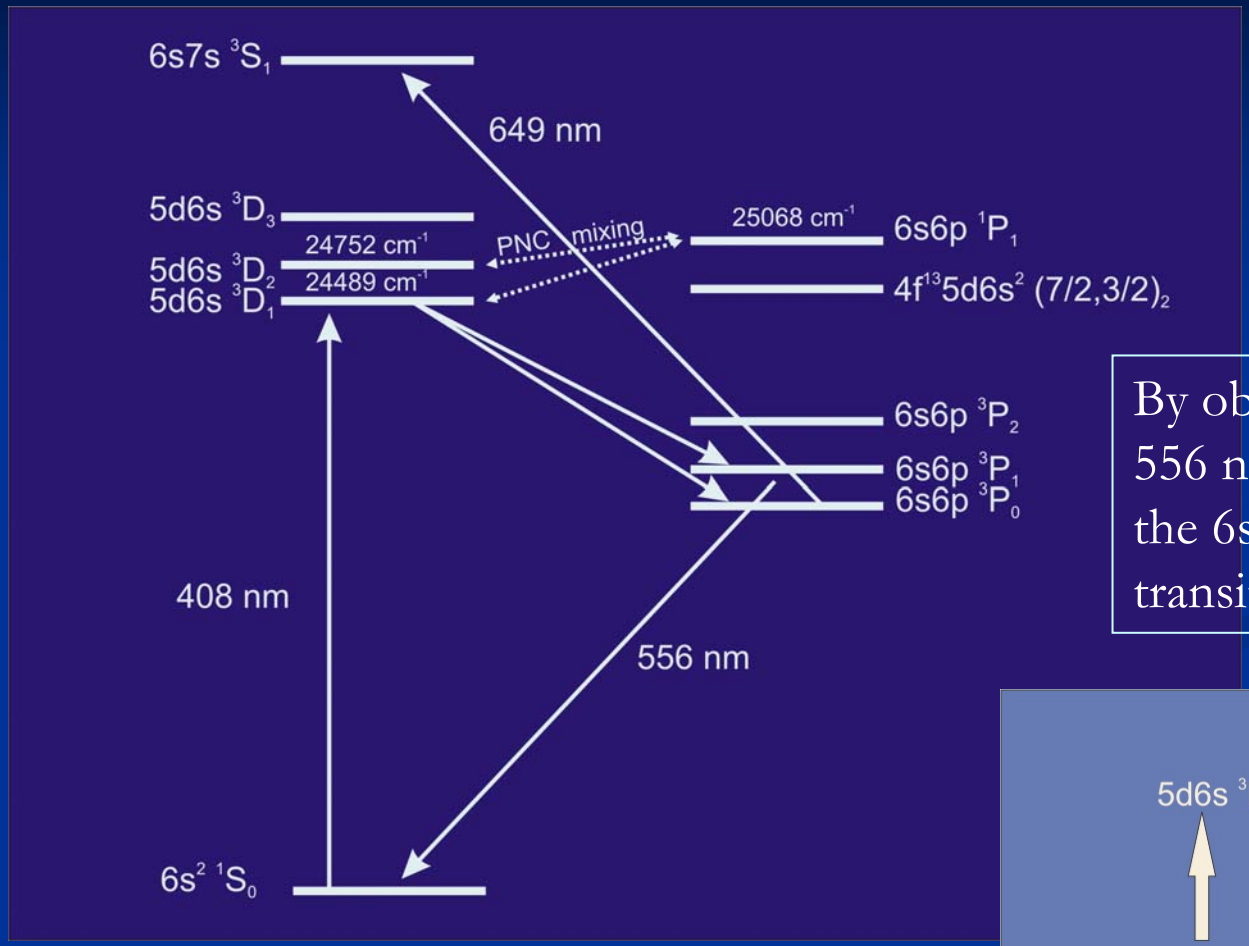
Anapole moment:

Unpaired proton	^{133}Cs $I=7/2$	^{205}Tl $I=1/2$
$\kappa_A \times 100$	36.4(6.2)	-22(30)

Ongoing experiments on APV

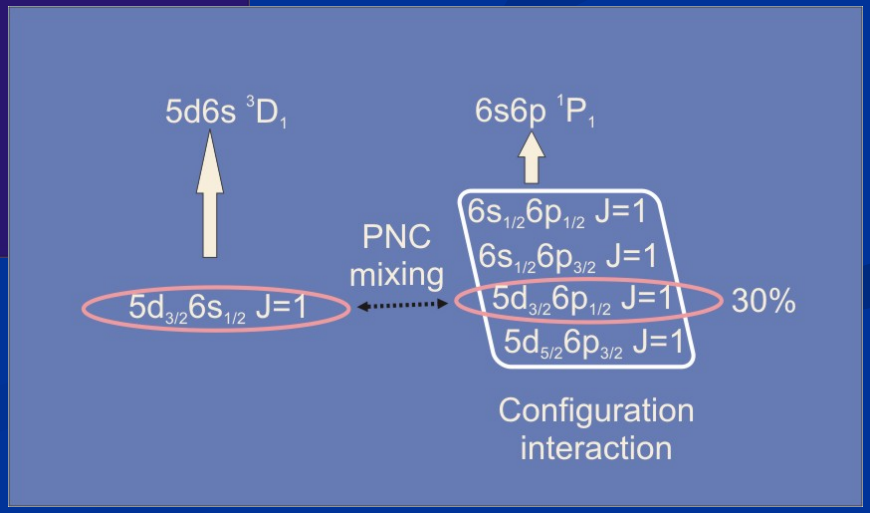
Group	Atom/Ion	Goal	Advantages	Status
Berkeley	Yb isotopic chain	Nuclear structure, anapole moment	A_{PNC} is a factor of 100 bigger than that of Cs. Seven isotopes.	Ongoing measurements
Seattle	Single trapped Ba^+ (Ra^+)	Q_W, anapole moment	Precise theory, A_{PNC} is a factor of 20 bigger than that of Cs. Nine stable isotopes, $\Delta N=8$	Preliminary exps. on RF spectroscopy of trapped ions
Stony Brook, Legnaro, Yale, TRIUMF (Vancouver)	Cold Fr	Anapole moment	Precise theory, bigger effect than that of Cs, trapped atoms	Preliminary exps. on trapping of Fr
Yale	Diatomic molecules	Anapole moment, C_2	A_{PNC} is enhanced due to proximity of the opposite parity levels. Level crossing .	Development of theory and exp. techniques

Atomic structure of Yb



Proposed by D. DeMille, PRL 1995

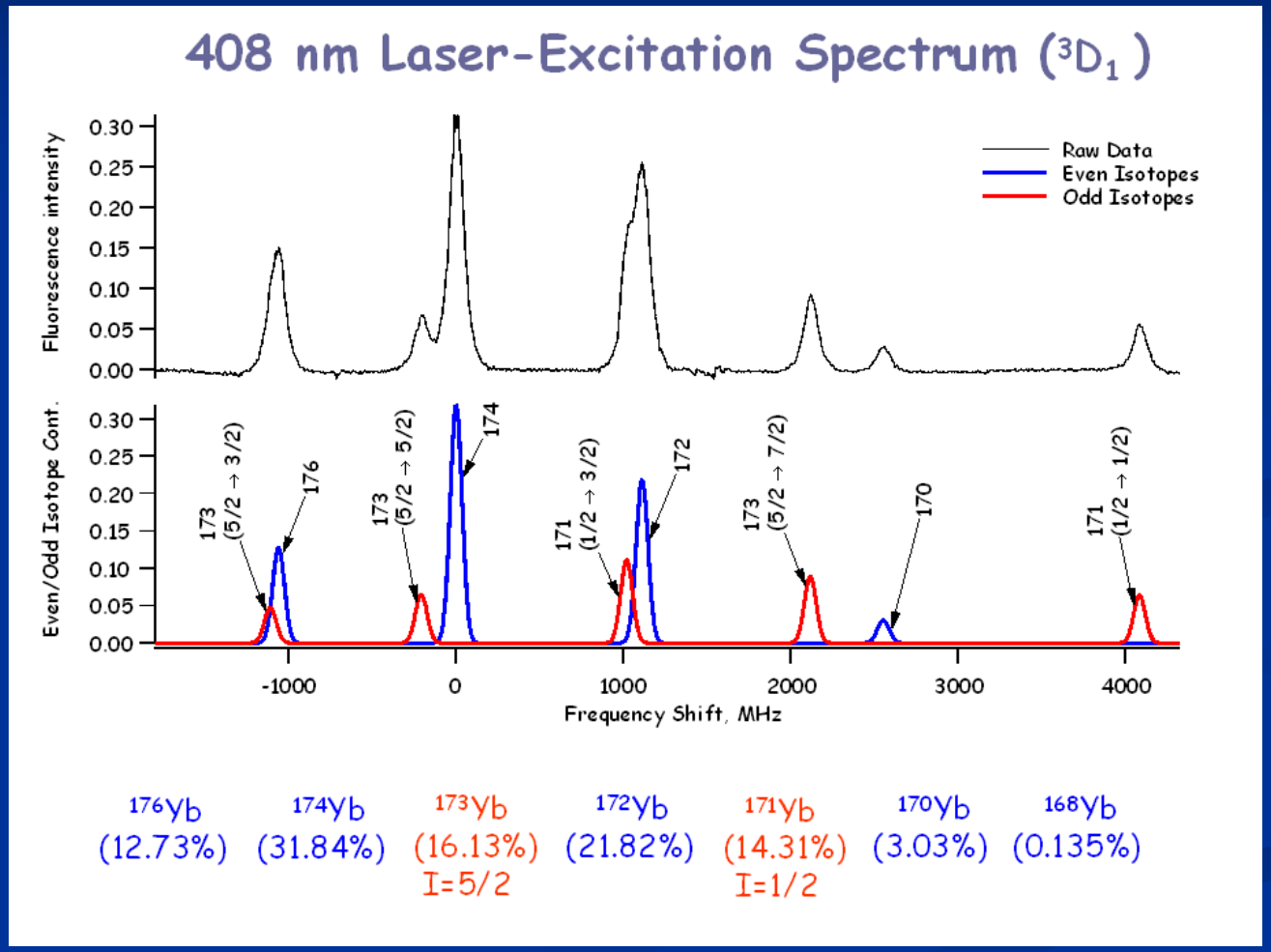
By observing the 6s^2 $^1S_0$ – 6s6p $^3P_1$ 556 nm decay the pumping rate of the 6s^2 $^1S_0$ – 6s5d $^3D_1$ 408 nm transition is determined.



In addition, the population of 6s6p $^3P_0$ metastable level is probed by pumping the 6s6p $^3P_0$ - 6s7s $^3S_1$ 649 nm transition.

Yb isotopes and abundances

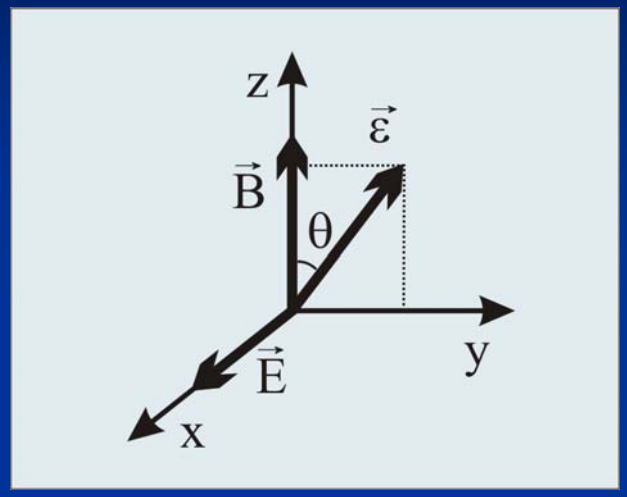
Seven stable isotopes, two have non-zero spin



C.J. Bowers et al, PRA 1999

Rotational invariant and geometry of the Yb experiment

Rotational invariant to which the PV-Stark interference term is proportional is chosen so that **E** is along the excitation light axis. This suppresses the interference between M1 and Stark amplitudes emphasizing the PV-Stark contribution.



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

Reversals:
B – even
E – odd
$\theta \rightarrow \theta \pm \pi/2$ – odd

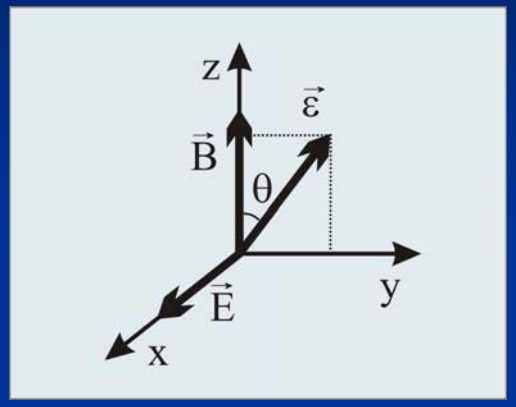
$$A^{q}_{Stark} = i\,\beta\,(-1)^{q}\left(\vec{E}\times\vec{\varepsilon}\right)_{-q}\left\langle j,m,1,m'-m \middle| j',m'\right\rangle$$

$$A^{q}_{PNC} = i\,\xi\,(-1)^{q}\,\vec{\varepsilon}_{-q}\left\langle j,m,1,m'-m \middle| j',m'\right\rangle;\;\; q = m - m'$$

$|\beta| = 2.24(25)\times10^{-8}$ e $a_0/(V/cm)$ – Stark transition polarizability (Measured by J.Stalnaker at al, PRA 2006)

$|\xi| = 1.08(24)\times10^{-9}$ $(Q_W/104)$ e $a_0/(V/cm)$ – Nuclear spin-independent PV amplitude (Calculations by Porsev et al, JETP Lett 1995; B. Das, PRA 1997)

PV effect on line shapes: even isotopes



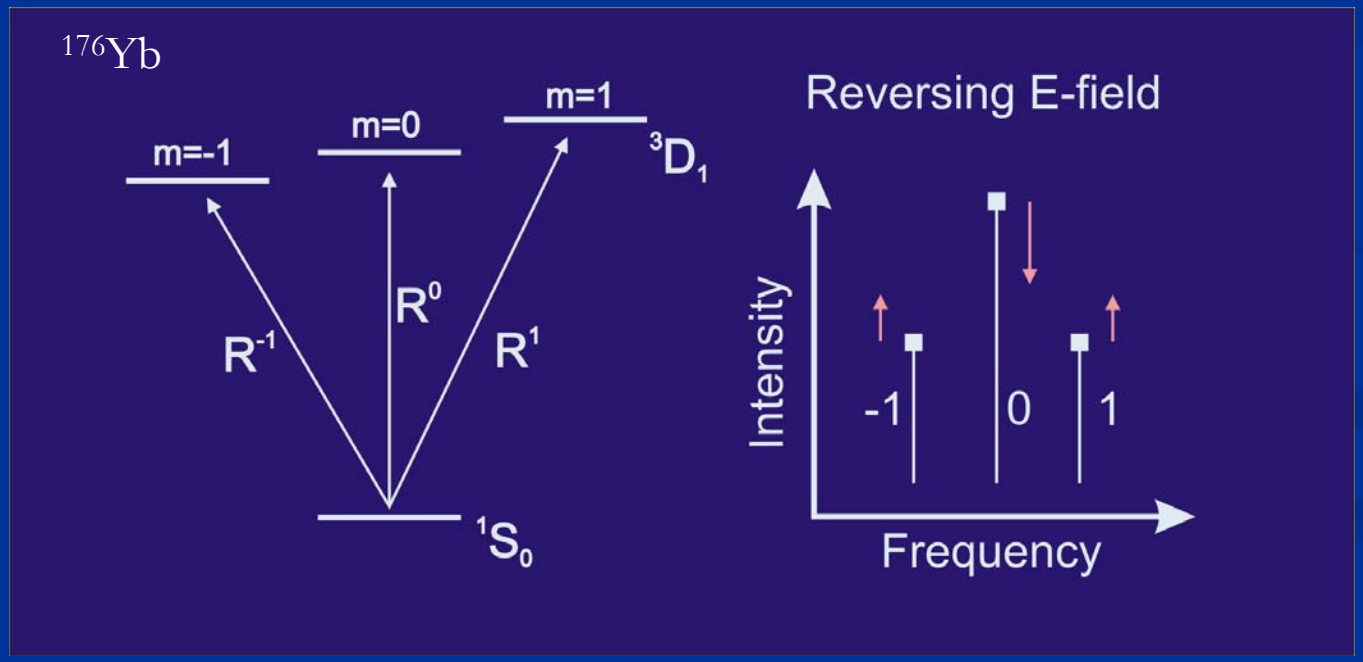
$$\vec{E} = (E,0,0)$$

$$\vec{\varepsilon} = (0,\sin\theta\ ,\cos\theta)$$

$$R^{0} = \beta^{2}\ E^{2}\ \sin^{2}\theta + 2E\ \beta\xi\sin\theta\cos\theta$$

$$R^{\pm 1} = \frac{\beta^{2}\ E^{2}}{2}\cos^{2}\theta - E\ \beta\xi\sin\theta\cos\theta$$

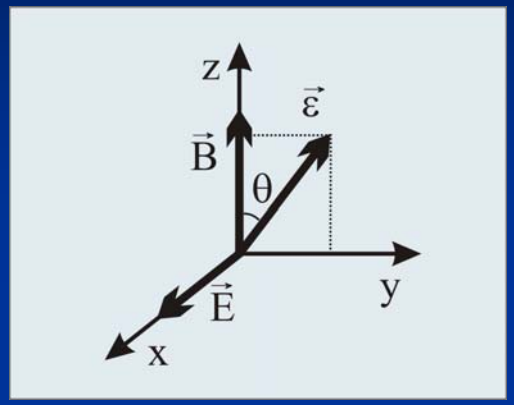
PV-Stark interference terms



Rate modulation under the E-field reversal yields:

$$\frac{R_{E+} - R_{E-}}{R_{E+} + R_{E-}} = \frac{2\xi}{\beta E}$$

PV effect on line shapes: odd isotopes

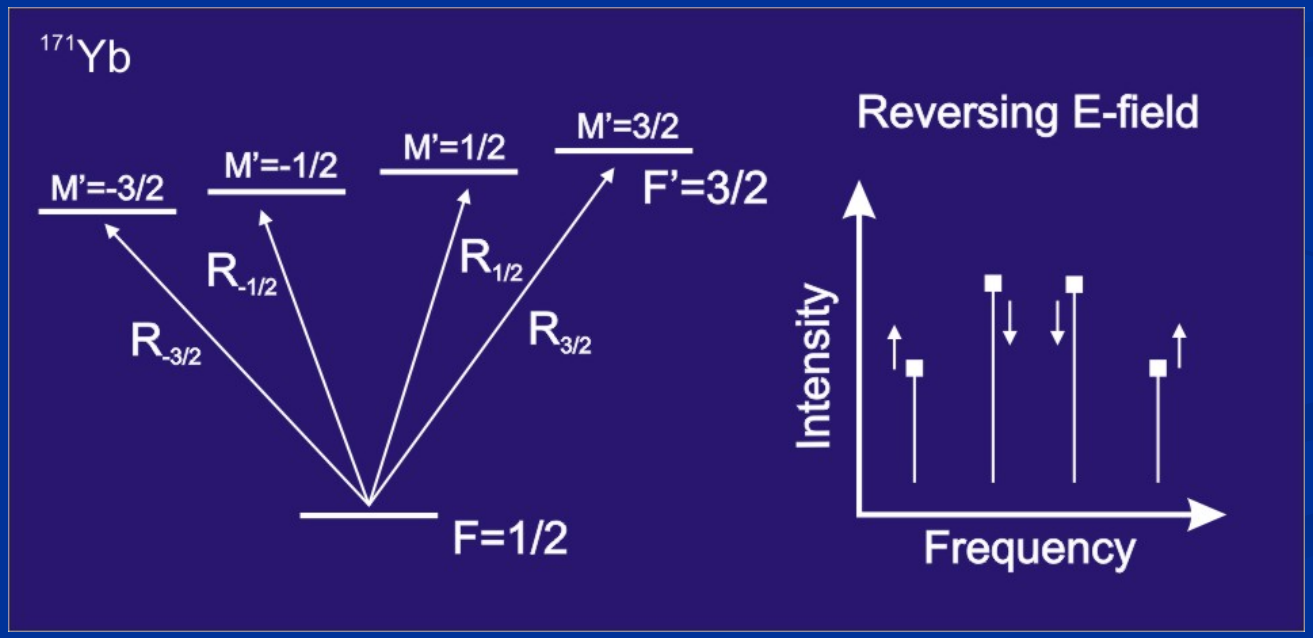


$$\vec{E} = (E,0,0)$$

$$\vec{\varepsilon} = (0,\sin\theta\ ,\cos\theta)$$

$$R^{center} = \frac{\beta_{FF'}^2 E^2}{6}(4\sin^2\theta + \cos^2\theta) + E\ \beta_{FF'}\xi'\sin\theta\cos\theta$$

$$R^{side} = \frac{\beta_{FF'}^2 E^2}{2}\cos^2\theta - E\ \beta_{FF'}\xi'\sin\theta\cos\theta$$



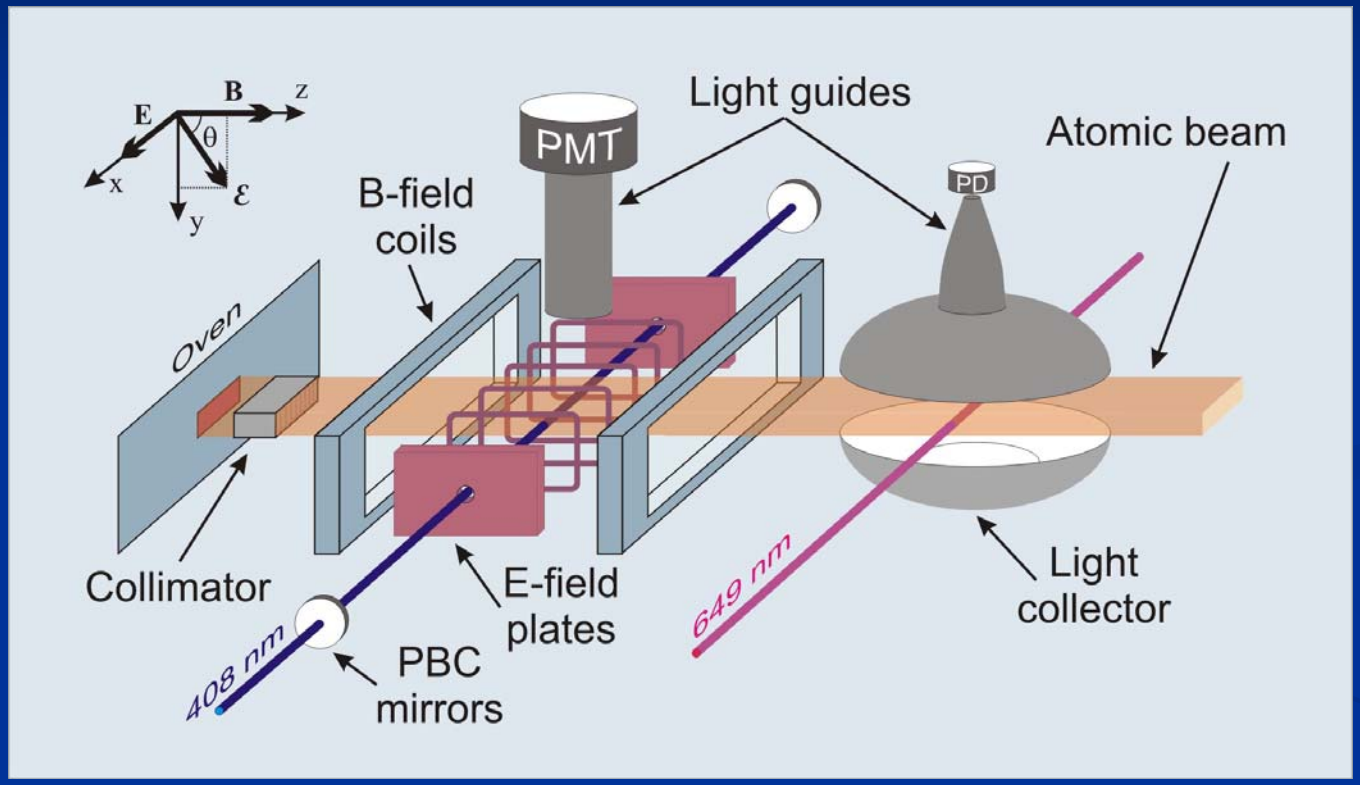
$$\xi' = \xi + \left\langle \vec{I}\cdot\vec{J} \right\rangle\ \xi^{NSD}$$

$\xi^{NSD} \approx 10^{-12}$ ea_0 for odd Yb isotopes

$\xi = 10^{-9}$ ea_0

ξ` must be measured with 0.1% accuracy

Experimental setup



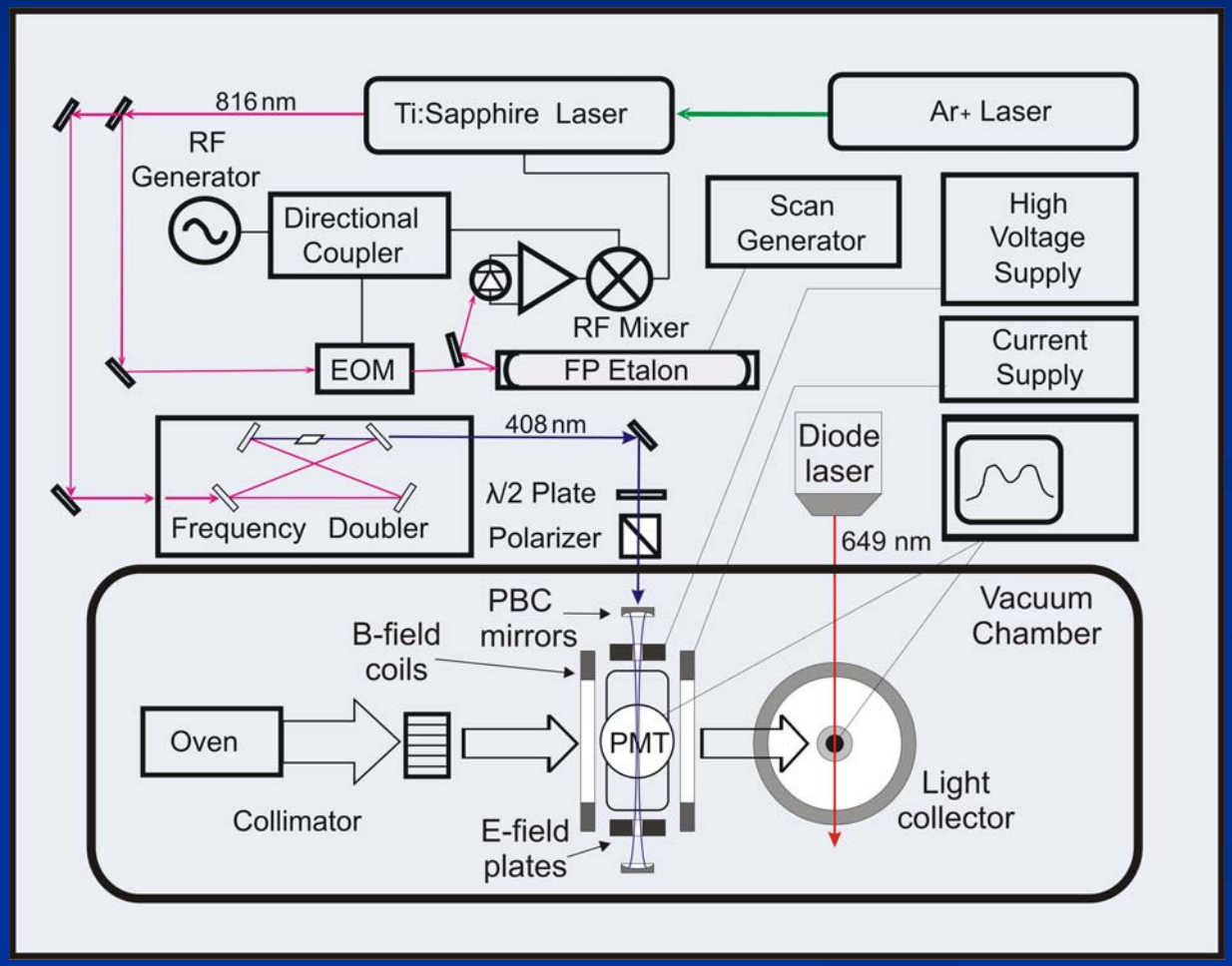
Light collection efficiency:

Interaction region: ~0.2% (556 nm)

Detection region: ~25%

Yb density in the beam ~10^{10} cm^{-3}
Reversible E-field up to 15 kV/cm, spatial homogeneity 99%
Reversible B-field up to 100 G, homogeneity 99%

Optical system and control electronics

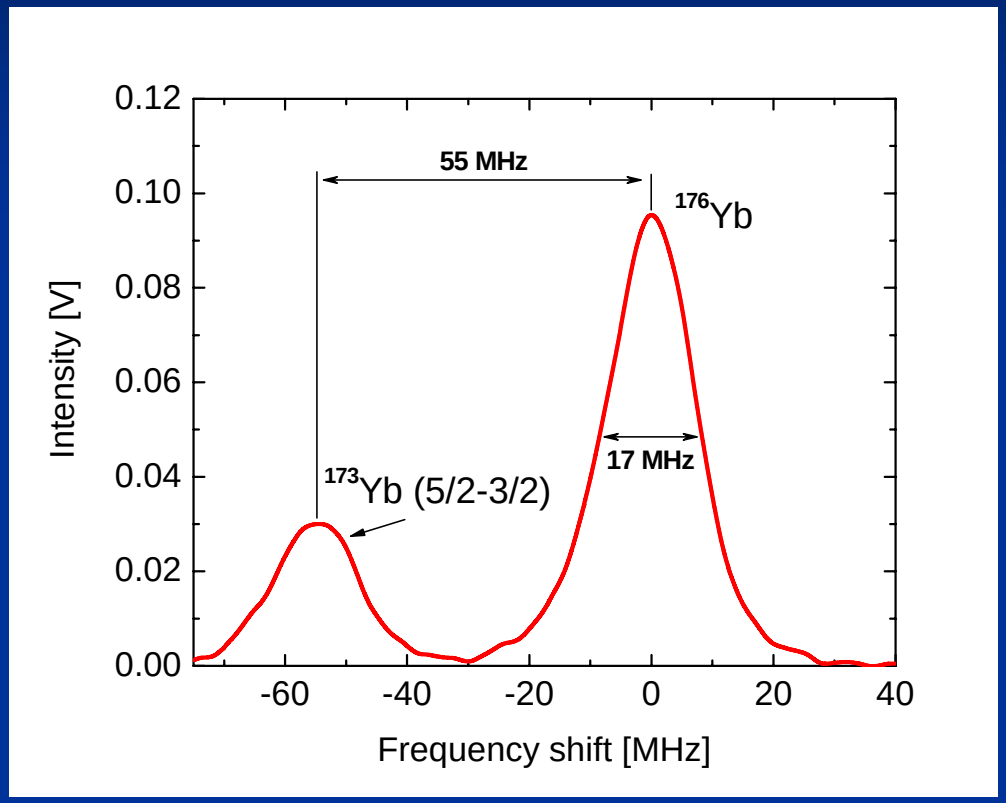


Light powers:
Ar^+: 15W
Ti:Sapp (816 nm): 1W
Doubler (408 nm): 50 mW

PBC:
Confocal design, 25 cm;
Finesse ~4000
(upgrading to 40000)

Locking:
Pound-Drever-Hall technique

Doppler width and spectral resolution

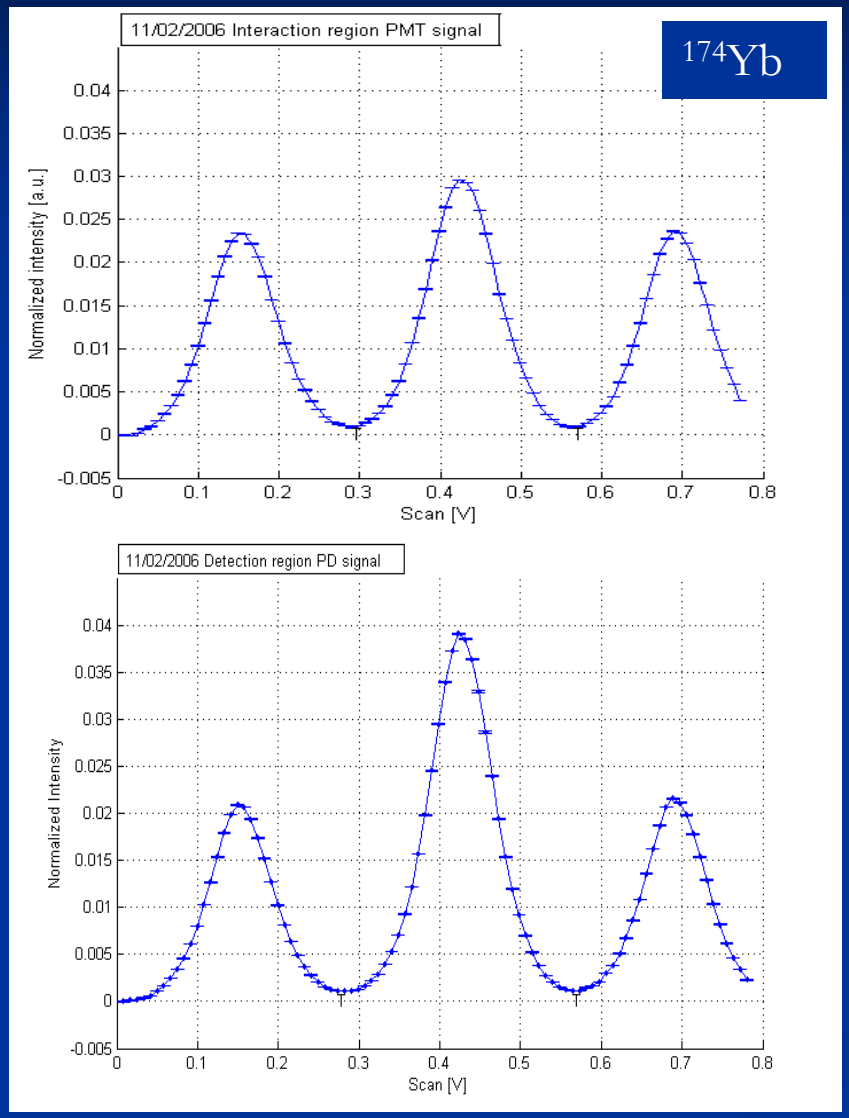


Application of the atomic beam collimator allows to reduce the Doppler broadening by a factor of 10 .

Spectral lines of closely neighboring isotopes can be clearly resolved.

Scanning over 408 nm line, observing 556 nm fluorescence at the interaction region.

Line shapes under the B-field



Under application of B-field line profiles demonstrate predicted shapes

Signal averaged over 100 scans

Scan rate = 1 Hz

Ready to collect data with E-field reversals

Systematic effects

$\vec{E} = (E, dE_y, dE_z)$ E-field inhomogeneity

$\vec{B} = (dB_x, dB_y, B_0)$ B-field inhomogeneity

$\vec{\varepsilon} = (0, e^{idC}(\sin\theta + d\theta\cos\theta), \cos\theta - d\theta\sin\theta)$ Distortion of linear polarization of the light

$\vec{dk}$ Residual light propagation in the PBC

M1~300ξ

$$A_{\Sigma}^{q} = (-1)^{q}\left(i\beta\left(\vec{E}\times\vec{\varepsilon}\right)_{-q} + M1\left(\vec{dk}\times\vec{\varepsilon}\right)_{-q} + i\xi\,\vec{\varepsilon}_{-q}\right)\left\langle F, m, 1, m'-m \middle| F', m'\right\rangle$$

Terms having same dependence on the leading E-field reversal and same polarization angle dependence as the Stark-PNC interference term must be limited

$$\beta\frac{dB_x}{B}dE_y << \xi$$

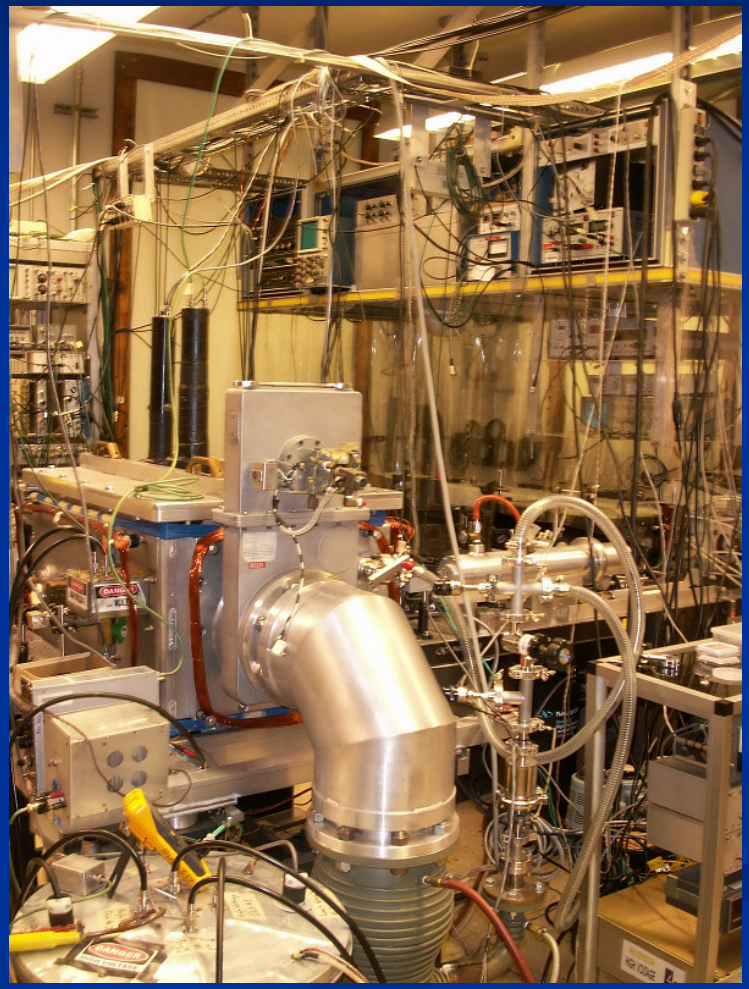
$$\beta\, dC\, dE_z << \xi$$

Required:

Non-reversing dB_x, dE_z << 1%

Summary

- The program of measurements needed to understand the system is complete
- It is now possible to proceed with confidence towards a first measurement of APV in Yb
- The challenge will then be to refine the system to achieve the fractional precision needed to observe NSD effects



Timeline

Berkeley experiment:

½ yr	A_{PV} enhancement, A_{PV}:10%
1 yr	Q_W in single Yb isotope, A_{PV}:1%
1½ yr	Q_W in chain of Yb isotopes, A_{PV}:0.1%
2 yr	Anapole moment

ElectroWeak Workshop