Atomic Parity Violation
Early days, present results, few prospects

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EARLY DAYS
Parity Operator: \[ \psi(\vec{r}) \xrightarrow{P} \psi(-\vec{r}) \]

\[ P \equiv (\text{Symmetry }/x,y \text{ plane}) \times (\pi \text{ Rot }/z \text{ axis}) \]

Equivalent to mirror symmetry or « left-right » symmetry

«Parity Violation» = «Breaking of mirror symmetry» in physical processes

1956: LEE et YANG were first to express doubts about mirror symmetry in weak interactions (e.g. \( \beta \) radioactivity)

And also to indicate how to make significant tests:

- Compare the results of two Mirror. Exp. (let 2 initially symmetric systems have a free evolution under the effect of the interaction to be tested)
  Determine whether there exists a left-right asymmetry in the results
- Measure a pseudoscalar physical quantity (ex. \( \vec{J} \cdot \vec{p} \))
Discovery of Parity Violation in weak interactions

One of the experiments suggested by Lee et Yang (1956)
Observation of $\beta$ decay for polarized nuclei $^{60}\text{Co}$ (1957)
The observed asymmetry is close to maximum!

Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, Columbia University, New York, New York
AND
E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson,
National Bureau of Standards, Washington, D. C.
(Received January 15, 1957)

Chien-Shiung Wu
An Atomic Preference between Right and Left

By the end of the 60’s this was looking very unlikely:

— an atom exhibits a high degree of symmetry
— is governed by EM interactions (No distinction between right and left)

However 10 years later large efforts were engaged in atomic tests:

— After all the atom is not a purely EM system:
— what can be expected from other interactions? …gravity, strong,
  in particular weak interactions: New ideas had started to develop around 1970

Can they perturb the orbits of electrons when they approach the nucleus? If so, PV occurs!

By the end of the 70’s certain experiments had failed to detect such PV:
  …a weak link in a chain of theoretical reasoning… Only a few years later,
  several groups confirmed in a few atoms the existence of atomic PV

Such results complemented the spectacular successes of the Standard Model
  unifying EM and weak theories: discoveries of the W’s and Z₀

Atomic Expts performed at much lower energy, test long distances
  & provide information of different nature
Why such a sudden motivation for testing PV in atoms?

**Key point**: Emergence of the electroweak theory accounting for both EM & W interactions in a single mathematically coherent theory.

**Before**: weak interactions considered as mediated only by the $W^\pm$ bosons which makes the atoms unstable so that it was taken for granted that weak interactions and the associated PV were not relevant to the physics of stable atoms.

**After**: **New fundamental prediction of the theory**:
Existence of a third heavy gauge boson carrying no electric charge, the $Z_0$ mediating a weak force: Neutral Current Interaction.

Nothing anymore prevents the electron in a stable atom to feel the $Z_0$ interaction.

When the search in atoms started (ENS1972), the NC discovery at Gargamelle was still looking extremely hypothetical and causing many questions to arise:
- Do NC exist with neutrinos or only with charged particles?
- If present in atoms the effect may be much too small to be detected? the range of the interaction is only $10^{-7}$ of the atomic radius!
The situation in 1976: as seen by Steve Weinberg

Information of two types:
1) there is no information yet about the existence of a neutral current interaction between electrons and atomic nuclei (important to discriminate standard model against vector model)
2) there is no direct evidence of parity violation in any kind of neutral current
In atoms L-R PV-asymmetries are exceedingly small $10^{-6}$ WHY?

In big contrast with $\beta$-decay

Both processes have identical initial and final states, and can interfere,

$$P_{L/R} = [A_{em} \pm A_w]^2$$

$$Asym = \frac{P_L - P_R}{P_L + P_R} = 2 \text{Re} \left( \frac{A_w^\text{odd}}{A_{em}^*} \right)$$

nothing similar in $\beta$-decay:

$$Asym \approx A_w^\text{odd} / A_w^\text{even}$$

$$q \approx h/\text{Bohr radius} \approx m_e \alpha c$$

$$Asym = \frac{g^2}{e^2} \frac{1}{q^2 + M_Z^2 c^2} \approx \frac{g^2}{e^2} \frac{\alpha^2 m_e^2}{M_Z^2} \approx 10^{-15}$$

But there are enhancement effects!
First enhancement effect: the $Z^3$ Law (M-A Bouchiat & C. Bouchiat 1974)

Penetrating orbital

Nucleus of charge $Z$

Coulomb orbital of radius $a_0/Z = 1/Zm_e\alpha c$

$$q^2 \approx (Zm_e\alpha c)^2$$

In addition the various nucleons add their contributions **coherently**

$$Asym \approx \frac{q^2}{M_Z^2 c^2} Z \propto Z^3$$

Even faster than $Z^3$ because of relativistic effects
Second enhancement effect: choose a highly forbidden transition in Cesium = the heaviest (stable) alkali: Z=55

A good compromise between high Z & simplicity of the atomic structure making reliable atomic physics calculations necessary for interpreting the result

$6S_{1/2} \rightarrow 7S_{1/2}$  single photon transition between two S states

QED $\Rightarrow E_1 \equiv 0$

The $Z_0$ exchange breaks the Parity selection rule

$E_1^{pv} \approx i \times 10^{-11} \times e a_0$

$M_1$ is allowed by symmetry

$M_1 \approx 4 \times 10^{-5} \times \mu_B / c$

$E_1^{pv}/M_1 \approx 0.5 \times 10^{-4}$

Transition rate $10^{-6}/s \Rightarrow$ one photon per 10 days!

Apply a dc electric field & measure interference with the Stark induced amplitude $\Rightarrow$ great flexibility!

$i$ results from the T-reversal invariance of the weak NC interaction and prevents existence of a static EDM in a stationnary state

(M-A Bouchiat & C. Bouchiat 1975) J. Physique(France) 36, 493
How work started in Cesium

We started theoretical work, Claude and I on the Cs suggestion, during fall 1972. In June 1973 an order was passed to Spectra Physics for a color center laser, 1st in France! Presentations started to be given: e.g. Trieste (A. Salam), seminars...

With Lionel Pottier we started the first set-up and, against all the odds, (at first no light at 540 nm!) we succeeded to validated the Stark interference method in 1976 by applying it to the measurement of the highly forbidden M1 amplitude J. Phys. (France) 37, L-79 (1976)

July 76: there was an animated session at the Atomic Physics Conference in Berkeley. I discovered that G. Commins with Steve Chu had started an expt on Tl 6P\(_{1/2}\) - 7P\(_{1/2}\) line. Big efforts were also engaged to search for an optical rotation signal on the Bi allowed M1 transitions. Before the end of 76, absence of a PV effect was announced by two groups...

Sept. 1979 Important workshop in Cargèse (W. Williams organizer)

C. Prescott reported first observation of a PV asymmetry in polarized electron scattering at high energies, \(1.5 \times 10^{-4}\) with 10% accuracy and without contribution of syst effect.

The three Bi groups presented positive results, some of them still preliminary. It emerged that first observation of a manifestation of weak interaction in a purely atomic process was achieved. But there was still a disturbing factor 2 discrepancy between Novosibirsk and the two other groups, Seattle and Oxford.

In Tl a two sigma effect was reported followed by a 3 sigma effect one year later.
Thallium: (PV Stark interfer effect) Berkeley $\frac{E_{1}^{pv}}{M_{1}}$

$(5.2 \pm 2.4) \times 10^{-3}$ PRL 42, 343 (1979)
$(2.8 \pm 1.0) \times 10^{-3}$ PRL 46, 640 (1981)

$1.73 \pm 0.26 \pm 0.07$ PRL 53, 968 (1984)

\[\text{E}_{1}^{pv} / \beta \text{ (mV/cm)}\]

Cesium: (PV Stark interfer effect) Paris $\frac{E_{1}^{pv}}{\beta} \text{ (mV/cm)}$

$-1.34 \pm 0.22 \pm 0.11$ Phys. Lett. 117B 358 (1982) 1st measurement

$-1.52 \pm 0.18$ 134B 463 (1984) 2nd combined with the 1st

Most precise result

Determination of $E_{1}^{pv}$ with 0.35% accuracy PRL 82, 2484 (1999) by the Boulder group

Using the absolute calibration procedure by $M_{1}^{hf}$ developed by the Paris group
First Cesium results 1982-83


6 sigma statistical accuracy

2nd measurement in 1983 on a different hf component with same accuracy (134B, 463)

Combining them leads to 12% accuracy for $E_1^{\text{PV}}$

At that time theoretical accuracy was 8 %

This provided a quantitative test of the standard model at low energies extending the range of $q^2$ where the theory finds experimental support by more than 7 orders of magnitude.

Model independent interpretation: complementarity with the high energy SLAC exp
PRESENT RESULTS
What is measured in Atomic Parity Violation experiments?

- "weak neutral current interaction": $Z^0$ boson exchange between the nucleus and electrons

$$V = V_{em} + V_{pv} = -\frac{Ze^2}{r_e} + \frac{Q_w g^2}{2r_e} \exp\left(-M_{Z^0} c r_e / \hbar\right) \left(\frac{\vec{\sigma}_e \cdot \vec{p}_e}{m_e c}\right) + \text{H.c.}$$

extra term in the atom's hamiltonian

- Mixing of opposite parity states: $|" + " > = |+ > + i\delta_{pv} |- >$,

- "charged current interaction"?

  Charge currents together with Neutral currents contribute to APV through the nuclear anapole moment

  ➤ nuclear spin dependant contribution to $V_{pv}$

  much smaller,

  identified by its dependance on the hyperfine transition)
Extracting the weak charge from the measured PV amplitude

\[ V_{pv} = \frac{Q_w G_F}{4\sqrt{2}} \delta^3(r_e) \left( \frac{\sigma_e \cdot \vec{p}_e}{m_e c} \right) + \text{H. C.} \]

\[ g^2 / M_{z_0}^2 \leadsto G_F = 4 \times 10^{-14} a_0^3 \]

Fermi constant very well known

only S-P mixing:
\[ |"nS"> = |nS> + i\delta_{pv} |n'P> \]

⇒ Selection rules \( <nS|d|n'S> = 0 \) are violated...

in cesium, \( <6s|d|7s> = i E_{1pv} \bar{\sigma}_e \propto (-i) 0.8 \times 10^{-11} |e|a_0 \)

from Expt

\[ E_{1pv} = \frac{Q_w}{\text{atomic factor}} \]

from At theory

**Cs:** calculations have reached the 0.5% accuracy level in 2005 and 0.27% in 2009

Using the most accurate Cs expt 0.35% (Boulder 1997), the present value of \( Q_w \)

Is now in perfect agreement with the prediction of the standard model.

⇒ **Cs** is the best choice among the stable atoms
What does one learn by measuring the weak charge?

Table-top Cs experiments + Atomic Theory
(1SD) Boulder 1999 & At Theory 2005
Polarized Electron Scattering (1SD)

Full constraint 95% CL
* Standard Model prediction

Constraints on the weak charges of the u and d quarks

\[ Q_A^W = -2 \left[ (2Z + N)C_{1u} + (Z + 2N)C_{1d} \right] \quad \text{from APV} \]
\[ Q_P^W = -2(2C_{1u} + C_{1d}) \quad \text{from } A_{LR} \text{ in PVES when } Q \rightarrow 0 \]
in the forward scattering limit
Table-top Cs experiments (1σd) Boulder 1999

& New Atomic Theory results (2009)

\( Q_w = -73.16(29)_{\text{exp}} \pm (20)_{\text{theor}} \) instead of \((36)_{\text{theor}}\)

Full constraint 95% CL slightly shifted

* Standard Model prediction

 Compared to the direct search of the \( Z' \) gauge boson searched at Tevatron collider yielding \( M > 0.82 \text{ TeV}/c^2 \) this new result implies \( M > 1.3 \text{ TeV}/c^2 \) (SO10 unification)

 The determination \( \sin^2 \theta^\text{eff}_W = 0.2381(11) \) becomes slightly better than the previous most precise low-energy test performed in the e-scattering expt at SLAC (2005) It is now in perfect agreement with the SM prediction
Confirmation of the predicted running of the electroweak coupling at low energies
Three contributions having the same structure

\[ V_2^{pv}(r) = G_F A_w \bar{\alpha} \cdot \vec{I} \ p_A(r) / 2\sqrt{2} \ I \]

**Contributions for Cs**

i) the nuclear anapole moment  
   dominant  
   0.09 to 0.16

ii) the axial contribution to the electroweak e-nucleon interaction  
   0.038

iii) Perturbation of the nuclear spin independent PV e-N interaction  
   by the hyperfine contact interaction which scales as
   \[ G_F Q_W e \mu_{Cs} / R_N \]  
   0.035

The uncertainty on the nuclear anapole moment reflects uncertainty on the \( g_N \)'s

**Theoretical prediction for Cs**

\[ \frac{E_1^{pv}(6S,F = 4 \rightarrow 7S,F = 3)}{E_1^{pv}(6S,F = 4 \rightarrow 7S,F = 4)} = 1 + \eta \]  

with \( \eta = 1.6 \pm 0.3\% \)

**Present status of the experiments**

One single measurement (Boulder 1997)

\[ \eta \approx 5 \pm 0.7\% \]

**A puzzling result!**
The nuclear anapole moment a qualitative description

\[
M^{\text{PV}}(r) = \beta \frac{\vec{r}}{|r|} \times M_s(r) \quad \text{a vector}
\]

\[
\vec{a} = 2\pi \int d^3r \, \vec{r} \times \vec{M}^{\text{PV}}(r) \quad \text{a pseudo vector}
\]

\[
H_{\text{ana}} = e \, \vec{\alpha} \cdot \vec{a} \, \delta^3(r) \quad \text{a contact PV interaction}
\]
The nuclear anapole moment theoretical prediction

One particle PV nuclear potential

\[ V_{N}^{pv} = \frac{1}{\sqrt{2}} G_F g_N \left( \vec{\sigma}_N \cdot \vec{p}_N / 2M_N \right) \rho_N(r_N) + h.c. \]

Coupling constant deduced from PV nuclear interactions

\[ V_{N}^{pv} \]

Can be eliminated by an infinitesimal gauge transformation at the price of a modification of the em current:

\[ J^{pv}(\vec{r}) \]

axial electric current of the nucleons which interacts with the electronic current

It is the Ampère current associated with \[ M^{pv}(\vec{r}) \]

\[ \vec{a} \]

Can be computed as the average value of a one-particle operator taken over the nuclear ground state \[ \langle N | M^{pv} | N \rangle \]


See the review paper Ginges & Flambaum Physics Reports 397, 63 (2004) for other calc.

The concept of «nuclear anapole moment» has been introduced first by Zel’dovich (1957)
Present Goals for Atomic Physics experiments

-- **Measure** \(Q_w\) **to 0.1% precision in Cesium** in view of the obtained gain of precision in atomic structure calculations. The Boulder result has to be cross-checked. Improvements are possible:
  - The Paris 2005 exp (2.5% accurate) has been interrupted while improving its statistics
  - A method taking advantage of a larger PV asymmetry amplification has been proposed
    
PRA 71, 042108 (2005) and JOSA B 22, 21 (2005)

-- **Devise feasible expts on francium** where the PV effect is 20 times larger but atoms are radioactive and scarce (S. Aubin)
  
  **Go ahead on the single Ra+ ion** experiment (KVI, talk of L. Willmann)

-- **Design an expt specifically sensitive to the nuclear spin-dependent PV effect**
  i.e. where the effect of the anapole moment dominates that of \(Q_w\)

-- **Make precise measurements of** \(\frac{E_{PV}^{1}}{E_{PV}^{2}}\) **ratios on different isotopes** (e.g. Yb)
  
  \(\Rightarrow Q_w\) and information about the neutron distribution
  
  \(\Rightarrow\) anapole moments for the two Yb odd isotopes (D. Budker)
Few Prospects
Can we find new strategies for APV measurements?

A suggestion inspired by the huge progress made in time and frequency metrology during the past ten years

PRL 100, 123003 (2008) and 98, 043003 (2007)

APV with Matter-Wave Interferometry

Up to now expts in forbidden transitions have been based upon Left-Right asymmetries in the transition rates (polarization-dependent).

A conceptual difficulty arises: metrologists use to measure frequency shifts

There is no frequency shift associated with a transition dipole

an electric dipole P-odd and T-even cannot give rise to a frequency shift in a stationary atomic state perturbed by homogeneous E and B dc fields (Sandars, 1977)

Solve the difficulty by using light shifts:

Place the Cs atoms in a radiation field quasi resonant with an atomic transition → a linear Stark Shift
Linear Stark shifts in dressed atomic states

Weak charge Stark shift

\[ \begin{align*}
7S_{1/2} & \rightarrow \delta_F \\
6S_{1/2} & \rightarrow \Delta W
\end{align*} \]

\[ \hbar \omega \]

Anapole Stark shift

\[ \chi = \hat{E} \wedge \xi \hat{k} \cdot \hat{B} \]

Chirality of the field configuration

Two dressed atoms with opposite chirality

\[ \begin{align*}
6P_{3/2} & \rightarrow \delta_{3/2} \\
6P_{1/2} & \rightarrow \Delta W \\
6S_{1/2} & \rightarrow \Delta W
\end{align*} \]

\[ \hbar \omega \]
Dressed Cs atoms behave similarly to enantiomer molecules

The chirality of the chemical site inside an enantiomer is replaced by the chirality of the field configuration …more easily controlled! Two mirror-image configurations give shifts of opposite signs.
PV linear Stark shift of the dressed Cs or Fr ground state

Linear in $E$ in $V_{pv}$ and quadratic in $\mathcal{E}$.

Time ordered diagrams:

Enhanced for photons near-resonant with $6S-6P$

$V_{pv}^{NSD}$

Anapole moment

Enhanced for photons near-resonant with $6S-7S$

$V_{pv}^{NSI}$

Weak nuclear charge

+ ... permutated order + h. c.
The anapole shift

A possible intermediate state provided $F' \neq F$

... but only for the *nuclear spin dependent* part

$< 6S_{1/2} F | V_{\text{ana}} | 6S_{1/2} F \pm 1 > \neq 0$

Enhancement of the shift if the photons are near-resonant with the 6S-6P transition

The weak charge shift

Is a possible intermediate state $\Rightarrow$ shift enhanced with photons close to the 6S - 7S transition frequency
The nS-n'S coupling exerted by the dressing beam transforms

\[ i \text{Im} E^{pu}_i(n, n') \tilde{\sigma} \]

into

\[ \frac{\alpha \mathcal{E}^2}{\hbar \delta_F} \text{Im} E^{pv}_i \xi \hat{k} \wedge \tilde{\sigma} \]

a transition electric dipole

\[ \frac{\hbar \Omega^2}{\Delta W \delta} d_I \xi \hat{k} \wedge \tilde{I} \]

a static one

both P-odd but T-even leading to freq. shift

Similarly the transition anapole EDM

\[ d_I s \wedge \tilde{I} \]

into

\[ \frac{\hbar \Omega^2}{\Delta W \delta} d_I \xi \hat{k} \wedge \tilde{I} \]

a static EDM

smaller than \( d_I \) but opening the route to frequency measurements and this in conditions where it dominates the weak charge effect

There is a price to be paid: instability of the ground state

This electric dipole is static at the time scale required for measurements provided experimental conditions be optimized in each case:

Adjust the dressing beam intensity for acceptable cold atom decay during \( \tau_i \)

& fulfill a compromise between \( E \) and dertuning:

Weak charge \( E \approx 100 \text{ V/cm}, \quad \delta/2\pi \approx 65 \text{ MHz} \) from the forbidden line \( \mathcal{E} \approx 2.2 \text{ kV/cm} \Rightarrow \tau_i \approx 1 \text{ s} \)

Anapole EDM \( E \approx 100 \text{ kV/cm}, \quad \delta/2\pi \approx 6.6 \text{ THz} \) from the resonance line
Measurement on a sample of cold francium atoms

Weak charge shift expected magnitude 100 μHz in Fr

\[ N_{at} = 10^6 \quad {}^{221}\text{Fr} \quad (I=5/2) \quad \text{Cold atoms} \]

First prepared in a MOT, then placed in an optical dipole trap (lin pol & far-blue detuned to avoid light shifts)

Ramsey atomic interferometry

✔ Preparation of a coherent state \( \left( |F, m\rangle + |F', m'\rangle \right)/\sqrt{2} \) with \( F \neq F', m = m' \), or \( F = F', m \neq m' \)

✔ Evolution during the interaction time \( \tau_i \) with the dressing beam

✔ Detection of the phase shift caused by this interaction
Sequence of measurements

1. Trap the atoms in a magneto-optical trap
2. Fill an optical dipole trap
3. Cool the atoms in the n=0 state of the trap
4. In a given E, B, ξk configuration measure ν_{HF} 18.6 GHz
5. Repeat in different configurations
6. Extract ν_{PV} odd in E, B, ξk 5 μHz in Cs, 100 μHz in Fr.
\[ \delta \nu = (1/2\pi \tau_i \sqrt{N_{at}}) \sqrt{T_c/\tau} \]

\[ \tau = \text{total measurement time,} \quad \tau_i \approx 1 \text{ s} \]

\[ T_c \approx 2\tau_i = \text{duration of one cycle} \]

\[ \Delta \nu^{po} = (\Gamma_{n'S} \tau_i)^{-1/2} \frac{\Omega^{po}}{2\pi} \]

\[ N_{at} = 10^6 \quad \text{for Fr} \]

\[ S/N = \frac{\Delta \nu^{po}}{\delta \nu} = \Omega^{po} \sqrt{\tau/2\Gamma_{n'S} \sqrt{N_{at}}} \approx 30 \text{ over one hour} \]

\[ S/N \propto \mathcal{E} \quad (\Rightarrow \text{Nat is equivalent to } \tau \text{ by the same factor}) \]

**Signature, Calibration & Syst effects**

- Several parameter reversals reduce drifts and syst effects:

\[ \text{sign}(\delta_F) \quad \text{sign}(m_F) \quad \text{sign}(\chi = \hat{E} \wedge \xi \hat{k} \cdot \hat{B}) \]

- Precise calibration is performed using the scalar light shift on the forbidden line by modulating the detuning: \( \pm \delta_F \)

\[ \Rightarrow \text{Ratio } \Delta \nu^{po}_{hf}/\Delta \nu^{ls}_{hf} \text{ Independent of the beam intensity and position} \]

- A small interaction region is favorable to a good control of the fields
Suppression of the M1 Stark shift: use another geometry

Dressing beam near-resonant with a $\Delta F = \pm 1$ transition

Detuning smaller than the excited state hf splitting $\delta_{FF'} < \frac{\beta}{\alpha} \Delta W(n'S)$

Linear polarization of the dressing beam

$\Rightarrow$ **Linear Stark shift** $\propto \vec{e} \cdot \hat{B} \left( \vec{e} \wedge \vec{E} \cdot \hat{B} \right)$

adjusting $E$ and $\delta_{FF'}$ properly, $\Rightarrow$ same magnitude of the shift

$\vec{E} \perp \vec{e}$ makes the nS-n'S scalar coupling absent

Interesting option: there is a PV shift on the 0-0 clock transition
Magnitude of the anapole shift

\[ \frac{d_f E \hbar \Omega^2}{\Delta W \delta} \]

Stability condition: not involving the Stark field

\[ \Omega^2 \leq \frac{\delta^2}{\kappa \Gamma_{P_{1/2}} \tau_i} \quad \delta \gg \Delta W \]

→ advantageous to \( \delta \) up to an optimum \( \Delta_{FS}/2.5 \); both P states contribute

\[ \frac{d_f E}{\hbar} = 30 \text{ mHz} \]

**In Cs**

\( E = 100 \text{ kV/cm} \)
\( \delta/2\pi = 6.65 \text{ THz} \)
\( \Omega_1/2\pi = 2.9 \text{ GHz} \quad B_{ls} = 0.24 \text{ G} \)

\( B \geq 0.5 \text{ G} \)

\( \Delta \nu_{ane} = 38 \mu\text{Hz} \)

for Cs atoms in a dipole trap

\(~10~times~more~for~Fr~\)

The signal obtained by modulating the differential scalar light shift allows one to eliminate \( \Omega_1^2 \) directly

\[ \frac{d_f E}{\Delta W} \]
Cold atom Interferometry is an impressive tool, still continuously improving, thanks to methods of cavity QED & Quantum Optics possibly using BE condensates.

Following this line PV experiments will present similarities with those searching for an e-EDM except for

- addition of the dressing beam with suitable wavelength, polarization, direction & intensity
- appropriate adjustment of the Stark field in magnitude and direction

### Comparison of magnitudes

**e-EDM**

*best present limit:*
Regan, Commins, Schmidt, DeMille (2002)
PRL 88, 071805 (2002)

Equivalent to a shift of **4 µHz** measured in Cs at 100 kV/cm

**Q_w**

In dressed Cs leads to a **5 µHz** Stark shift
In dressed Fr 100 µHz can be measured at 100 V/cm

anapole moment

In dressed Cs leads to a **40 µHz** Stark shift at 100 kV/cm

**Improving e-EDM limit or measuring PV light-shifts look of comparable difficulty**

(from strict point of view of stat. accuracy)
Concerning systematics, PV shifts have a more complete signature
Detrimental Effects
Can other frequency shifts perturb the measurement?

**Zeeman shift**: choose preferentially a linear-Zeeman shift independent transition
(e.g. 0-0 coherence with lin. Pol. // E)

**Collisional shift**: reduced by trapping the atoms in individual lattice sites

**Light shifts**:

✔ **Differential light-shift from the trapping beams** (6 kW/cm^2 at 532 nm): 33 Hz
  
  (reduced in the blue detuned trap $\langle I \rangle_{\text{trap}} = \frac{I_{\text{peak}}}{24}$)

✔ **Differential light-shift from the dressing beam without $E < 15$ Hz**
  (in case of a dressing standing wave, the trap and dressing intensities have to be properly adjusted to avoid deformation of the optical lattice by the dressing beam)

✔ **Stark and dressing beam induced light-shift**: about 3 Hz
  
  used to eliminate the uncertainty from isolated by $\delta_F$ modulation

The stability of those frequency shifts is required to be better than the projection noise over the period of the fastest reversal: shortening $T_c$ and $\tau_i$ can be helpful
Atomic P violation experiments at ENS Paris


**LAST EXPERIMENT**

«Measurement of the parity violating 6S-7S transition amplitude in cesium achieved within $2.6 \times 10^{-13}$ atomic-unit accuracy by stimulated-emission detection » Phys. Rev. A 71, 042108 (2005) and ref. therein (J. Guéna, M. Lintz, M.A. Bouchiat)


**ABSOLUTE CALIBRATION of E1pv using M1hf**


**FIRST EXPERIMENTS**

Detailed description of the experiment, M.A. Bouchiat, J. Guéna, L. Hunter, L. Pottier


«Observation of a Parity Violation in cesium», M.A. Bouchiat, J. Guéna, L. Hunter, L. Pottier


**INITIAL WORK**

Qw shift: nS-n’S near-resonant beam - Theoretical Description

$S$ states perturbed by $V_{Sark} = -D \cdot E$ and $V_{pv} = \frac{QwG}{4\sqrt{2}} (\delta^3(r) \bar{\sigma} \cdot \bar{v} / c + h.c.)$

Effective Dipole Operator acting between states $n\tilde{S}_{1/2}$ and $n'\tilde{S}_{1/2}$

$D^{ef}(n, n') = -\alpha(n, n')E - i\beta(n, n')\bar{\sigma} \wedge E - i \text{Im}E_{1}^{pv}(n, n')\bar{\sigma} + M_1\bar{\sigma} \wedge k$

$M_1 \approx 2 \times 10^4 \text{Im}E_{1}^{pv}$

Quantum description of the radiation field

circularly polarized laser beam: $e(\xi) = \frac{1}{\sqrt{2}}(e_1 + i\xi e_2)$

$N$ photon state $|N\rangle$ with energy density $\epsilon_0 \mathcal{E}^2 = N \hbar\omega/V$ in volume $V$

$|i\rangle = |n\tilde{S}_{1/2}\rangle |N\rangle$ and $|f\rangle = |n'\tilde{S}_{1/2}\rangle |N-1\rangle$

Combined atom-field eigen states

$\langle f|V_{rad}|i\rangle = -\frac{1}{\sqrt{2}} \mathcal{E} \langle n'\tilde{S}_{1/2}|e(\xi) \cdot D^{ef}|n\tilde{S}_{1/2}\rangle$

Calculation of the shift by time-independent perturbation theory
Special tools for taking up the challenge

✔ Intense **tunable laser** at 539 nm (with a narrow spectral width)
   500 mW cw laser  completely new in 1973
   or 1-2 mJ / pulse at 120 Hz

✔ Amplification of the beam by **multipassages** (ENS 1982)
   or in a FP cavity (100 000 Boulder 1997)
   or of the signal by stimulated emission (ENS 2003)

✔ Pure polarization states of the excitation beam
   explored with a **polarization modulator** (ENS 1982)

✔ **Decisive step**: used in all exp. so far
   Application of a **static electric field** assisting the transition:
   allows one to adjust at will the degree of forbiddenness of the transition