Atomic Parity Violation
Early days, present results, few prospects

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EARLY DAYS

PARITY

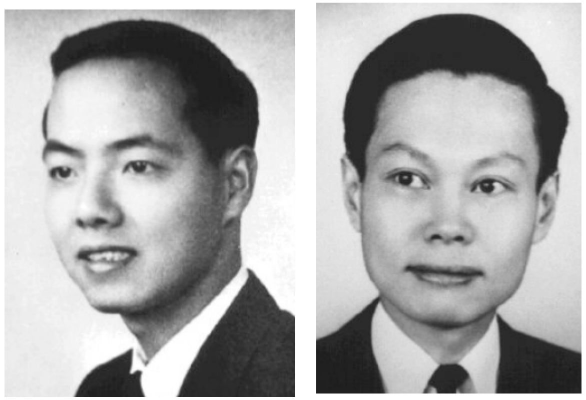
Parity Operator : $\psi(\vec{r}) \xrightarrow{\mathbf{P}} \psi(-\vec{r})$

$\mathbf{P} \equiv$ (Symmetry /x,y plane) x (π Rot /z 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. β radioactivity)



And also to indicate how to make significant tests :

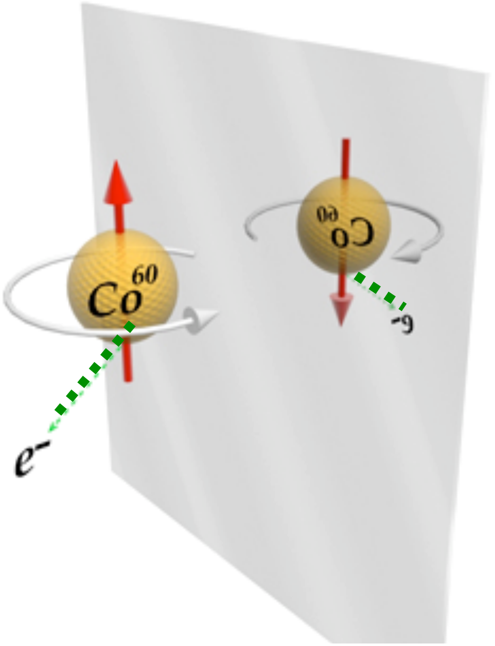
- Compare the results of two **Mirror. Exp**. (let 2 initially symmetric systems have a free evolution under the effect of the interaction to be tested)

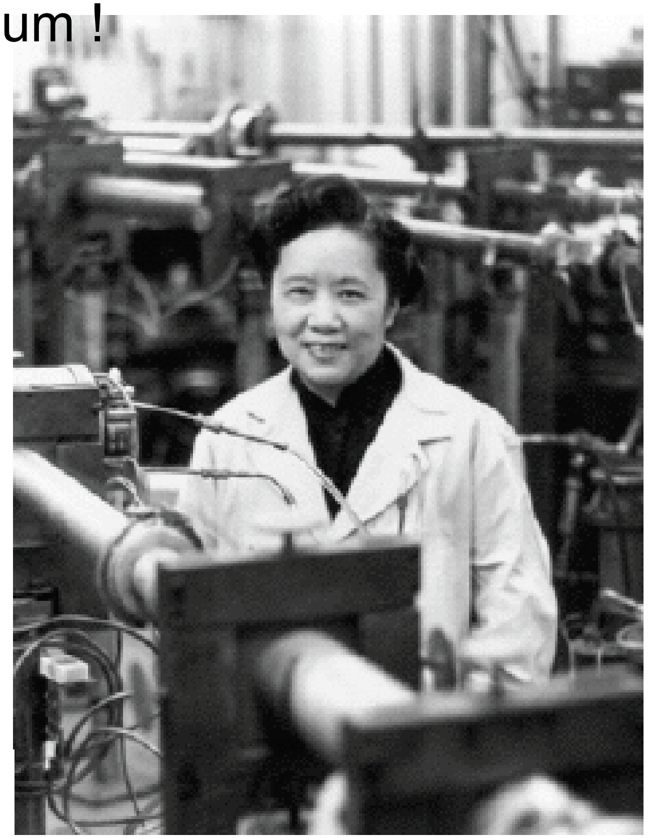
  Determine whether there exists a **left-right asymmetry** in the results

- Measure a pseudoscalar physical quantity (ex. $\vec{\mathbf{J}} \cdot \vec{\mathbf{p}}$

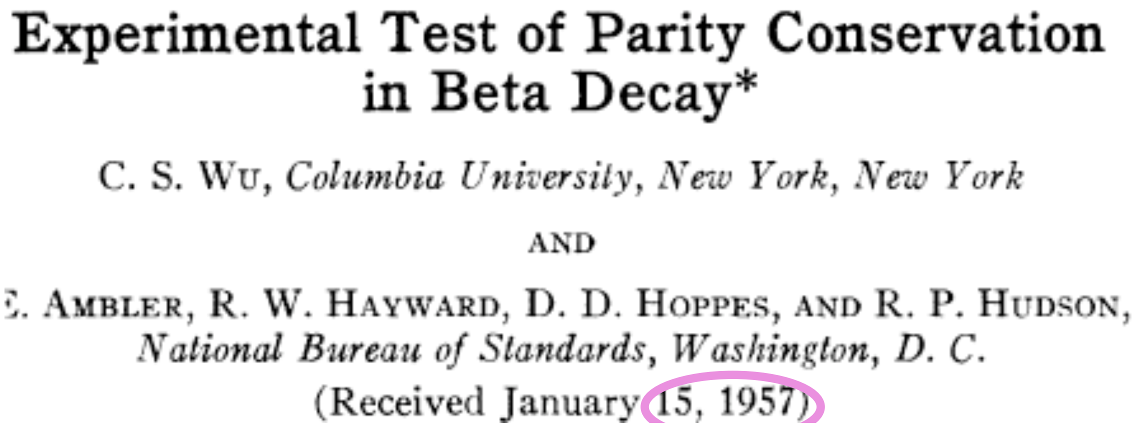
Discovery of Parity Violation in weak interactions

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





Chien-Shiung Wu



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)

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 failedd 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 Z_0

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

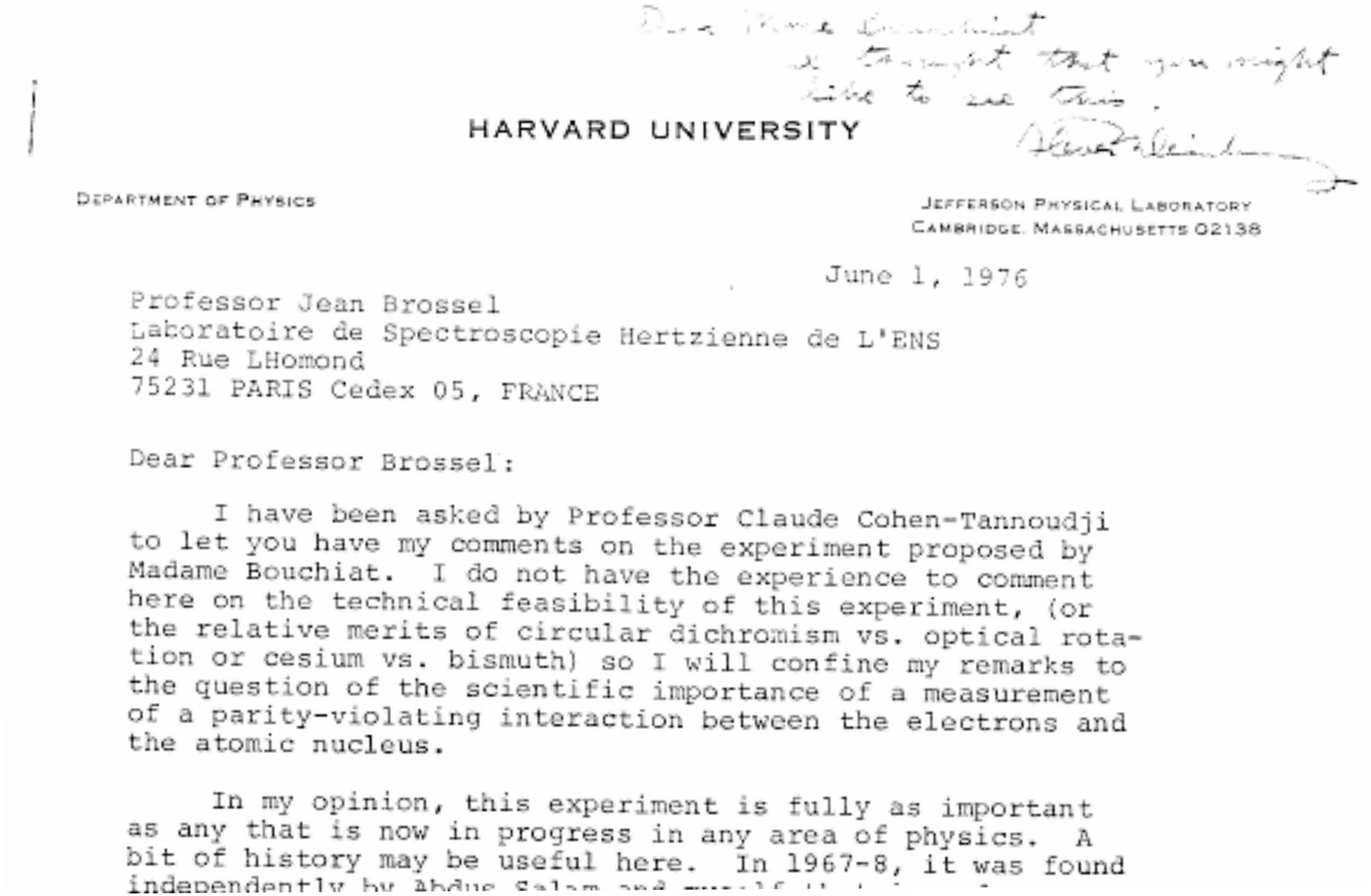
After: New fundamental prediction of the theory:
Existence of a third heavy gauge boson carrying no electric charge, the Z_0 mediating a weak force: Neutral Current Interaction

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



Dear Marie Bouchiat
I thought that you might
like to see this.
Steve Weinberg

HARVARD UNIVERSITY

DEPARTMENT OF PHYSICS

JEFFERSON PHYSICAL LABORATORY
CAMBRIDGE, MASSACHUSETTS 02138

June 1, 1976

Professor Jean Brossel
Laboratoire de Spectroscopie Hertzienne de L'ENS
24 Rue LHomond
75231 PARIS Cedex 05, FRANCE

Dear Professor Brossel:

I have been asked by Professor Claude Cohen-Tannoudji to let you have my comments on the experiment proposed by Madame Bouchiat. I do not have the experience to comment here on the technical feasibility of this experiment, (or the relative merits of circular dichromism vs. optical rotation or cesium vs. bismuth) so I will confine my remarks to the question of the scientific importance of a measurement of a parity-violating interaction between the electrons and the atomic nucleus.

In my opinion, this experiment is fully as important as any that is now in progress in any area of physics. A bit of history may be useful here. In 1967-8, it was found independently by Abdus Salam and myself

There is a lack of crucial information which could come out from At. Phys. Exp.

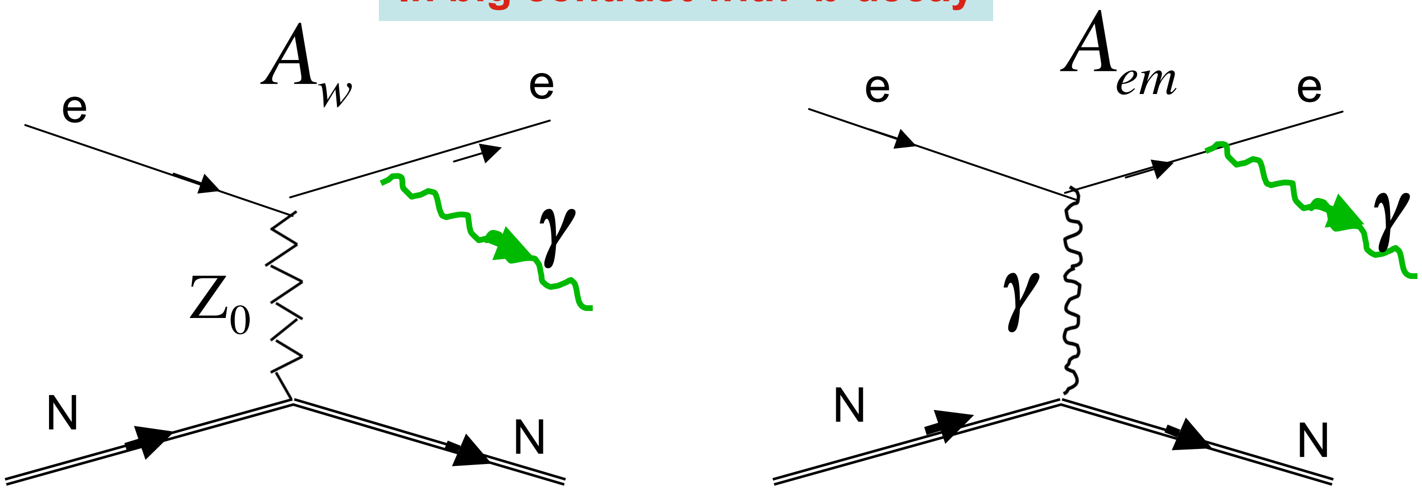
Information of two types:

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 ß-decay



Z_0 exchange competes with photon exchange

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

$$P_{L/R} = [A_{em} \pm A_w]^2 \qquad Asym = \frac{P_L - P_R}{P_L + P_R} = 2\,\mathrm{Re}(A_W^{odd} / A_{em}^*)$$

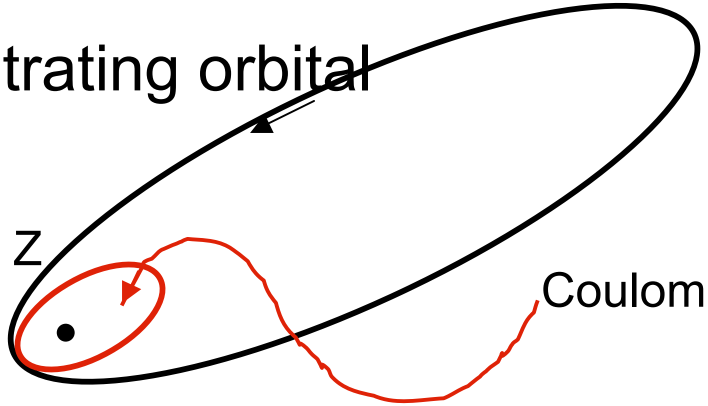
nothing similar in ß-decay : $Asym \approx A_w^{odd} / A_w^{even}$

$$\vec{q} = \vec{p}_e^{\,out} - \vec{p}_e^{\,in} \qquad q \approx h/\ Bohr\ radius \approx m_e \alpha\, c$$

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

But there are enhancement effects!

First enhancement effect: the $\mathbf{Z}^3$ Law (M-A Bouchiat & C. Bouchiat 1974)



Penetrating orbital

Nucleus of charge Z

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

$$\mathbf{q^2 \approx (Zm_e\alpha c)^2}$$

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

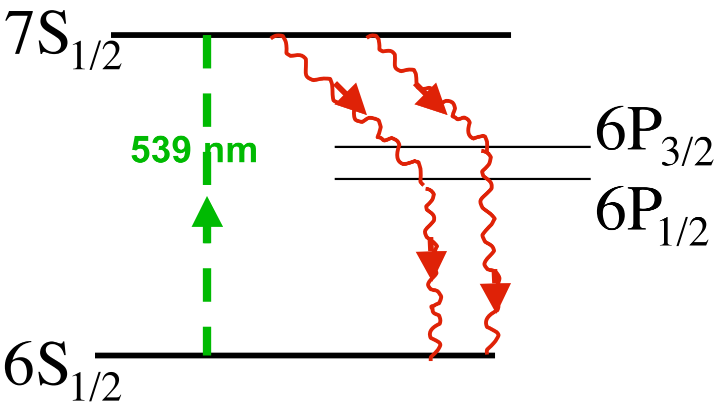
Second **enhancement effect:** choose a highly forbidden transition

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 ➔ $E_1 \equiv 0$



The Z0 exchange breaks the Parity selection rule

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

M_1 is allowed by symmetry

$$\mathbf{M_1} \approx 4 \times 10^{-5} \times \mu_\mathbf{B} / \mathbf{c}$$

$$\mathbf{E}\,{}_\mathbf{1}^{\mathbf{pv}} / \mathbf{M_1} \approx 0.5 \times 10^{-4}$$

Transition rate 10^{-6}/s ➔ one photon per 10 days !

Apply a dc electric field & measure interference with the Stark induced amplitude

➔ great flexibility ! (M-A Bouchiat & C. Bouchiat 1975)

J. Physique(France) **36**, 493

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

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, 1.5×10^{-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.

Early results

Thallium: (PV Stark interf effect) Berkeley E_1^{pv} / M_1

(5.2 ± 2.4) x 10^-3 PRL **42,** 343 (1979)
(2.8 ± 1.0) x 10^-3 PRL **46**, 640 (1981)

$E_1^{pv} / \beta\ (\mathrm{mV/cm})$

$1.73 \pm \underset{\overset{\uparrow}{\text{stat}}}{0.26} \pm \underset{\overset{\uparrow}{\text{syst}}}{0.07}$ PRL **53**, 968 (1984

Cesium: (PV Stark interf effect) Paris $E_1^{pv} / \beta\ (\mathrm{mV/cm})$

-1.34 ± 0.22 ±0.11 Phys. Lett. **117B** 358 (1982) 1st measurement

- 1.52 ± 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

1st measurement ENS 1982, J. Guéna, L. Hunter,L. Pottier, MAB (Phys. Lett. **117B**, 358)

6 sigma statistical accuracy

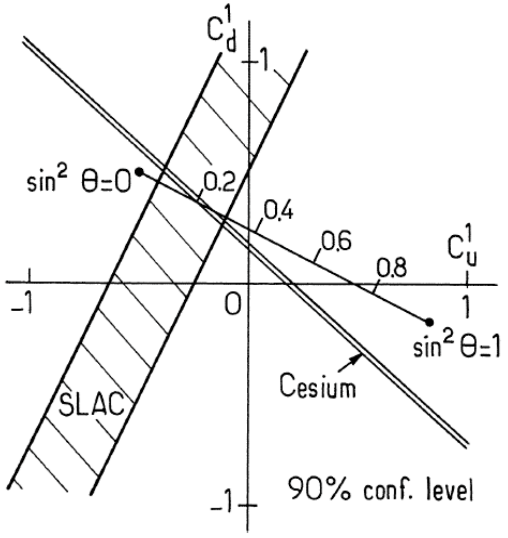
2nd measurement in 1983 on a different hf component with same accuracy (**134B**, 463)

Combining them leads to 12% accuracy for E_1^{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.

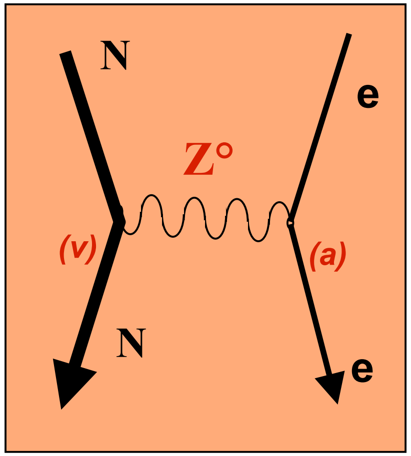
Model independent interpretation : complementarity with the high energy SLAC exp



SLAC + 1984 Cs result

PRESENT RESULTS

What is measured in Atomic Parity Violation experiments ?



- " **weak neutral current** **interaction "**: **Z° boson exchange**

  between the nucleus and electrons

$$V = V_{em} + V_{pv} = \frac{-Ze^{2}}{r_{e}} + \underbrace{\frac{Q_{w}\, g^{2}}{2r_{e}} \exp(-M_{z^{\circ}} c r_{e}/\hbar)\ \left(\frac{\vec{\sigma}_{e}\cdot\vec{p}_{e}}{m_{e}\, c}\right)}_{\text{extra term in the atom's hamiltonian}} + \mathrm{H.c.}$$

➔ **Mixing** of **opposite parity** states : $|\text{" + "}\rangle \;=\; |+\rangle + i\delta_{pv}\, |-\rangle$,

- " **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

Weak charge

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

$$g^2 / M^2_{Z0} \longleftrightarrow G_F = 4 \times 10^{-14} a_0^3$$

Fermi constant
very well known

only S-P **mixing**:
$| \text{"}nS\text{"} > \, = \, | nS > \, + \, i\delta_{pv} \, | n'P >$

➔ **Selection rules** ($<nS| \mathbf{d} | n'S> = 0$) are **violated…**

in cesium, $<\underline{6s}| \mathbf{d} | \underline{7s}> = i \, E_1^{pv} \, \vec{\sigma}_e \approx (-i) \, 0.8 \times 10^{-11} \, |e| a_0 \quad {}_e$

from Expt

$$E_1^{pv} = Q_W \times \text{atomic factor}$$

from At theory

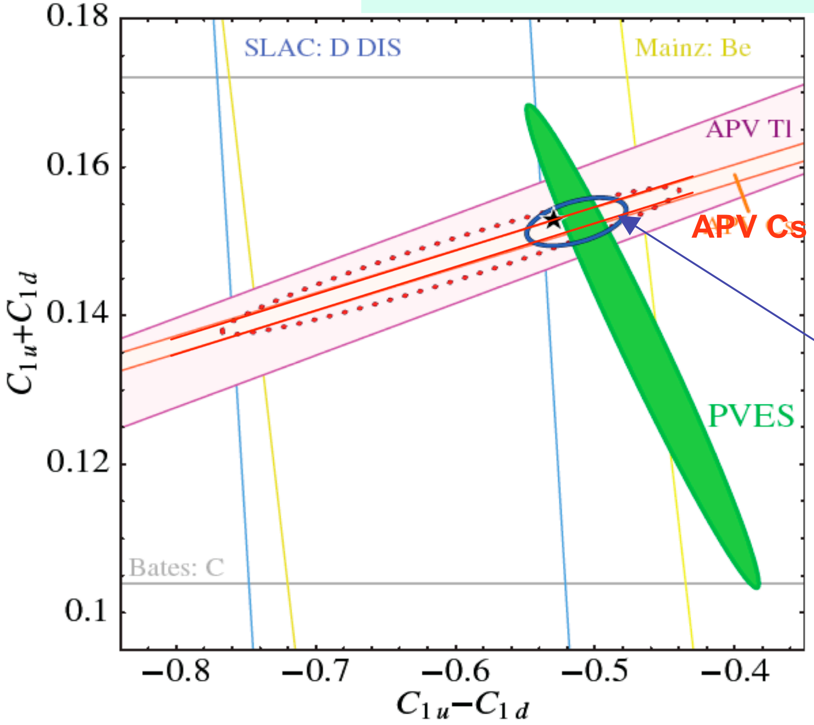
Cs: calculations have reached the 0.5% accuracy level in 2005 and 0.27% in 2009

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?



R.D.Young, R.D. Carlini, A.W. Thomas,J. Roche PRL **99,** 122003 (2007)

Table-top Cs experiments + Atomic Theory

(1SD) Boulder 1999 & At Theory 2005

Polarized Electron Scattering (1SD)

Full constraint 95% CL

*Standard Model prediction

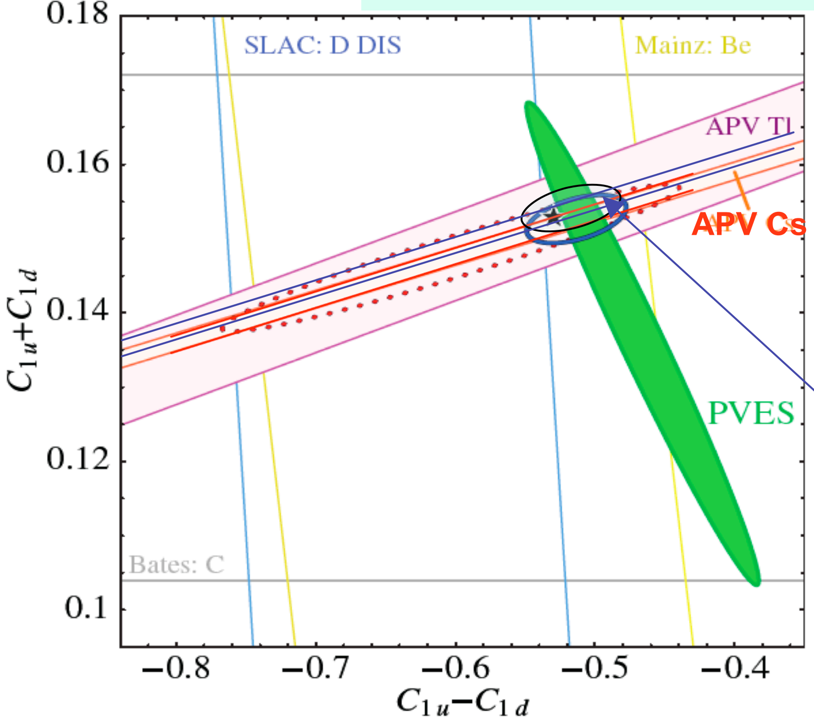
Constraints on the weak charges of the u and d quarks

$$Q_W^A = -2\left[(2Z+N)C_{1u} + (Z+2N)C_{1d}\right] \qquad \text{from APV}$$

$$Q_W^p = -2(2C_{1u} + C_{1d}) \qquad \text{from } A_{LR} \text{ in PVES when } Q \to 0$$

in the forward scattering limit

The weak charge: New Atomic Theory results 2009



S.G. Porsev, K. Beloy, A. Derevianko,
PRL 102, 181601 (2009)

Table-top Cs experiments (1SD)
Boulder 1999

& New Atomic Theory results (2009)

Q_W= -73.16(29)$_{exp}$ (20)$_{theor}$
instead of (36)theor

Full constraint 95% CL slightly shifted

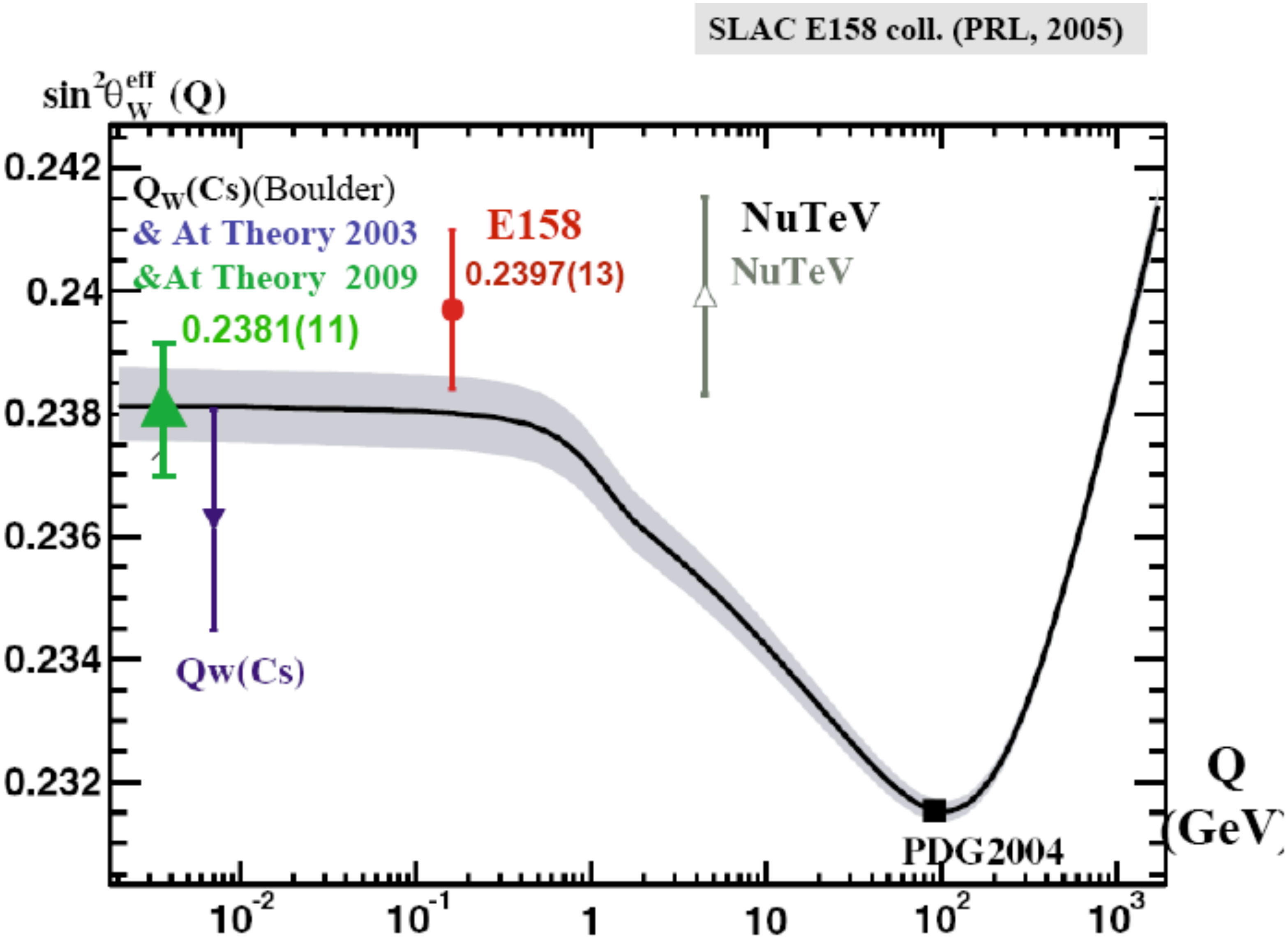
*Standard Model prediction

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

✔ The determination $\boxed{sin^2\theta_W^{eff} = 0.2381(11)}$ 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



Nuclear-spin dependent PV interaction   Present result

Three contributions having the same structure $V_2^{pv}(\mathrm{r}) = G_F\, A_W\, \vec{\alpha}.\vec{I}\ \ p_A(\mathrm{r})\ /2\sqrt{2}\ I$

	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 $G_F\, \mathrm{Q_W}\ e\mu_{Cs}/R_N$	0.035

The uncertainty on the nuclear anapole moment reflects uncertainty on the g_N's

Theoretical prediction for Cs : $\dfrac{\mathrm{E}_1^{\mathrm{pv}}(6\mathrm{S,F}=4 \rightarrow 7\mathrm{S,F}=3)}{\mathrm{E}_1^{\mathrm{pv}}(6\mathrm{S,F}=4 \rightarrow 7\mathrm{S,F}=4)} = 1+\eta$ **with** $\eta = 1.6 \pm 0.3\%$

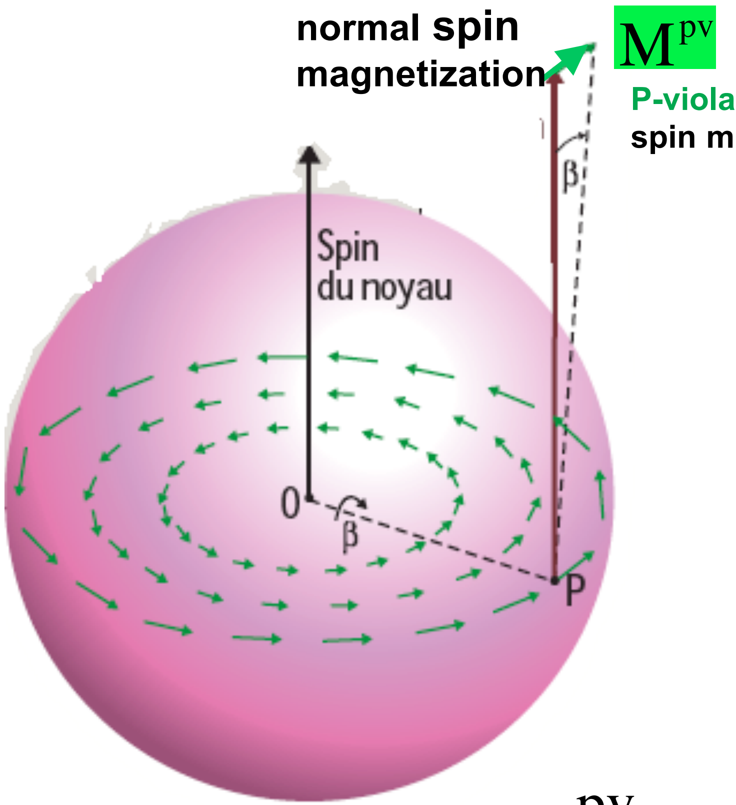
Present status of the experiments

One single measurement (Boulder 1997)

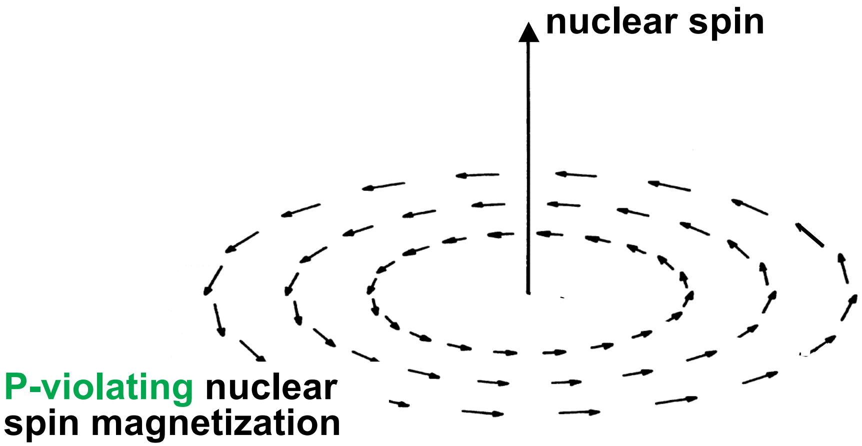
$$\eta \approx 5 \pm 0.7\%$$

A puzzling result !

The nuclear anapole moment a qualitative description



P-violating nuclear spin magnetization



$$M^{pv}(r) = \beta \frac{\vec{r}}{r} \times M_S(r)$$

a vector

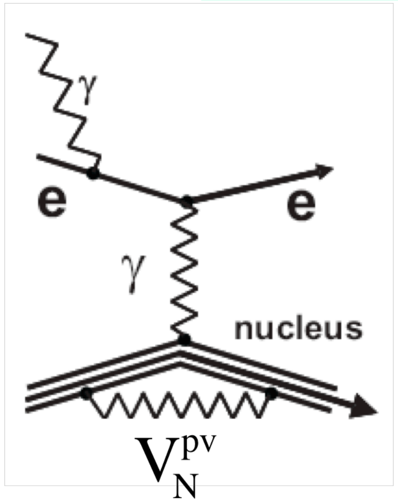
$$\vec{a} = 2\pi \int d^3r\ \ \vec{r} \times \vec{M}^{pv}(r)$$

a pseudo vector

$$H_{ana} = e\ \vec{\alpha}\ .\ \vec{a}\ \ \delta^3(r)$$

a contact PV interaction

The nuclear anapole moment theoretical prediction



One particle PV nuclear potential

$$V_N^{pv} = \frac{1}{\sqrt{2}} G_F\, g_N \frac{\vec{\sigma}_N . \vec{p}_N}{2M_N} \rho_N(r_N) + h.c.$$

Coupling constant deduced from PV nuclear interactions

(long range meson exchange dominates

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 $\langle N | M^{pv} | N \rangle$

Approach followed by C. Bouchiat & C.A. Piketty Z. Phys. C **49**, 91 (1991)
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** E_1^{pv} **ratios on different isotopes** (e.g. Yb)
➔ Q_w and information about the neutron distribution
➔ 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)

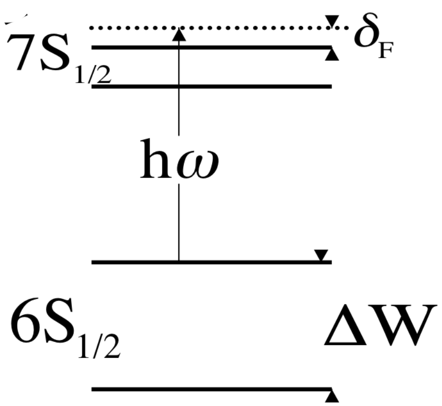
Solve the difficulty by using light shifts:

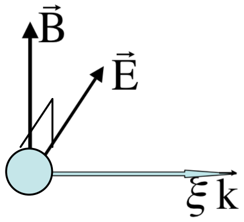
Place the Cs atoms in a radiation field quasi resonant with an atomic transition

➔ a linear Stark Shift

Linear Stark shifs in dressed atomic states

Weak charge Stark shift

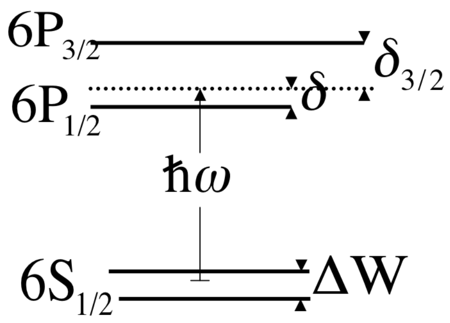




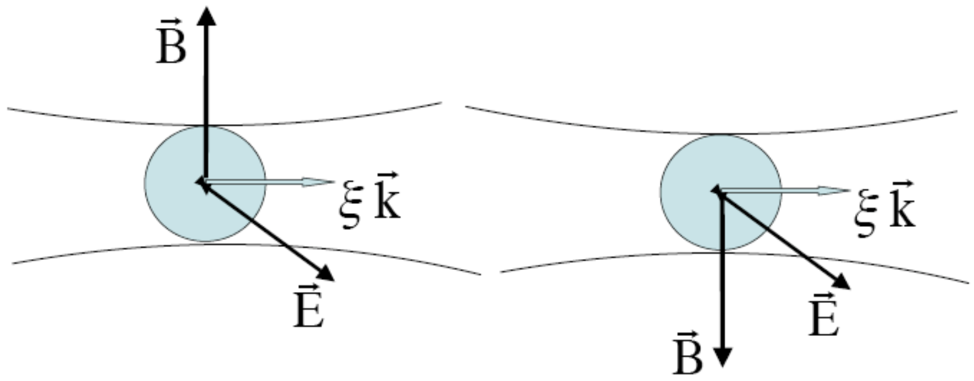
$$\boxed{\chi = \hat{E}\wedge\xi\hat{k}\cdot\hat{B}}$$

Chirality of the field configuration

Anapole Stark shift



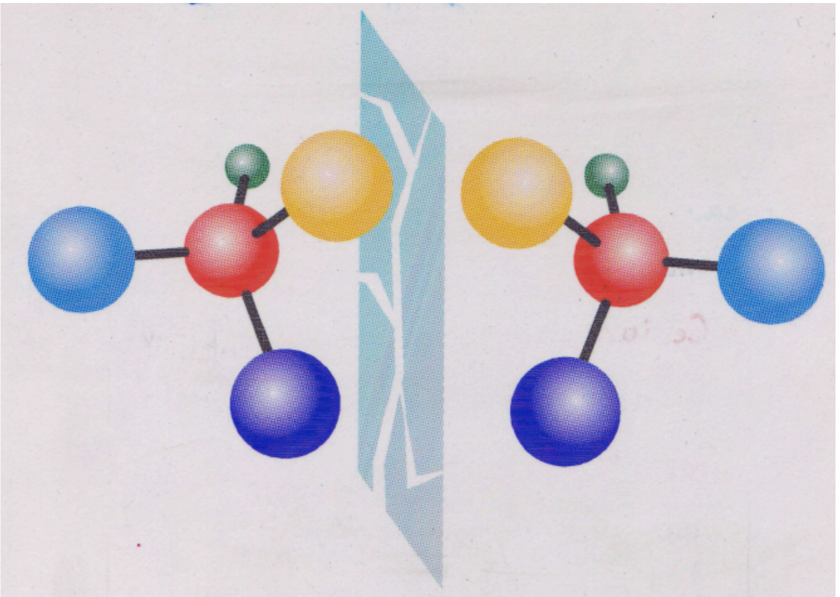
Two dressed atoms with opposite chirality



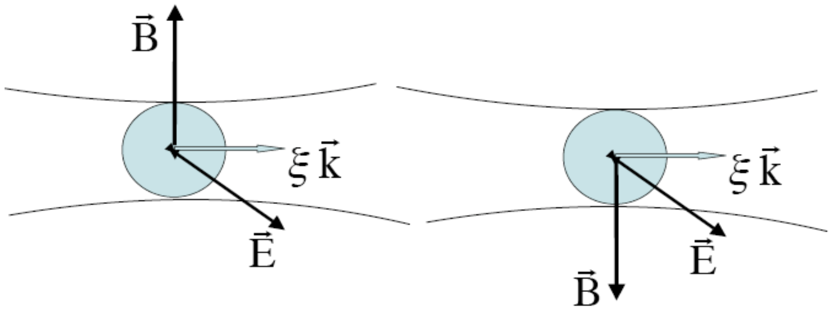
Dressed Cs atoms behave similarly to enantiomer molecules

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.



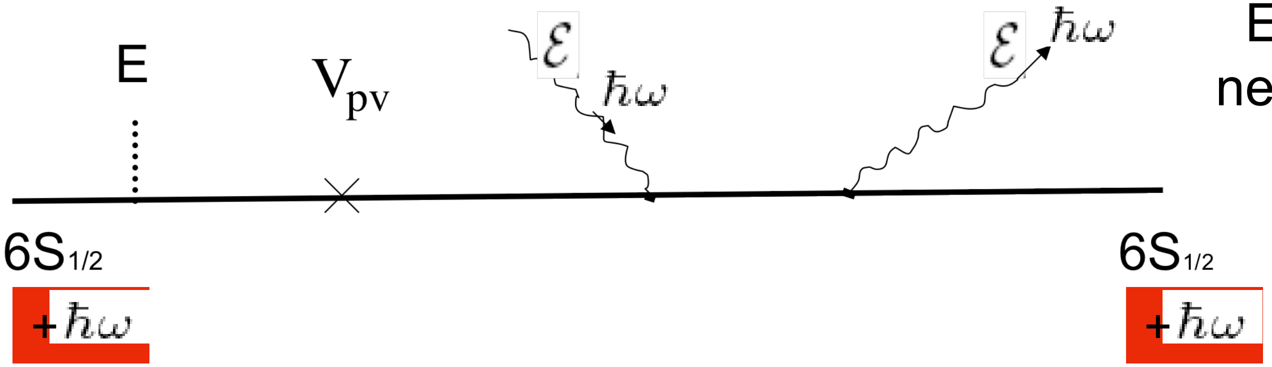
Dressed atoms of opposite chirality



PV linear Stark shift of the dressed Cs or Fr ground state

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

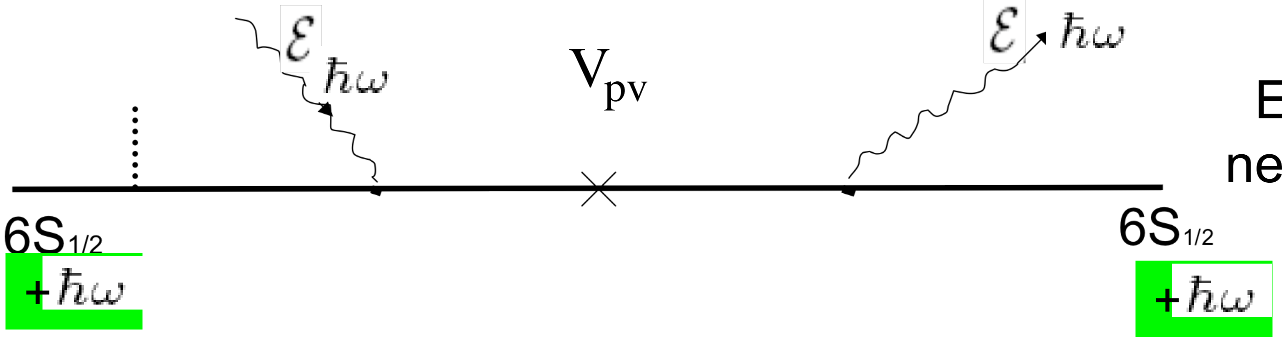
Time ordered diagrams:



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

V_{pv}^{NSD}

Anapole moment



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

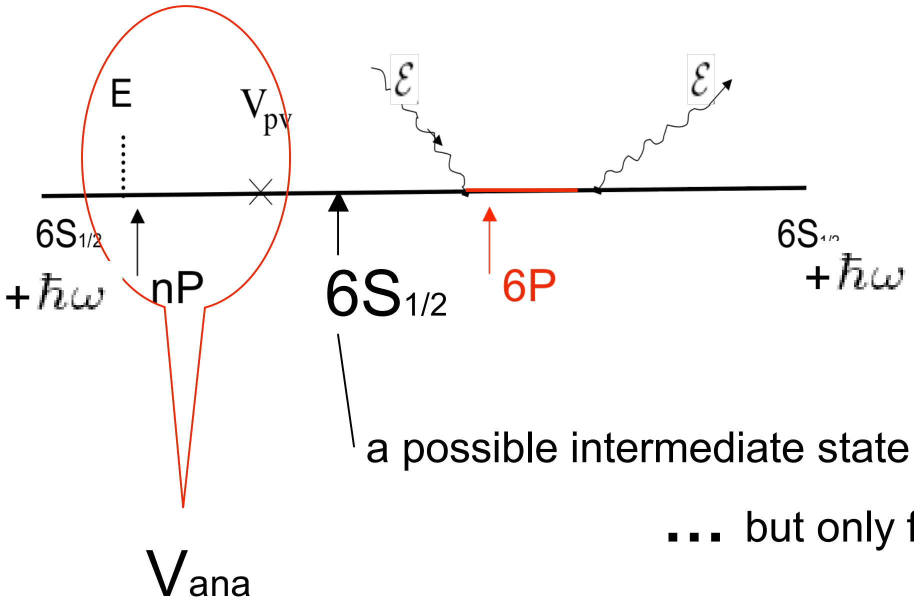
V_{pv}^{NSI}

Weak nuclear charge

+ … permutated order + h. c.

Two kinds of shifts

The anapole shift



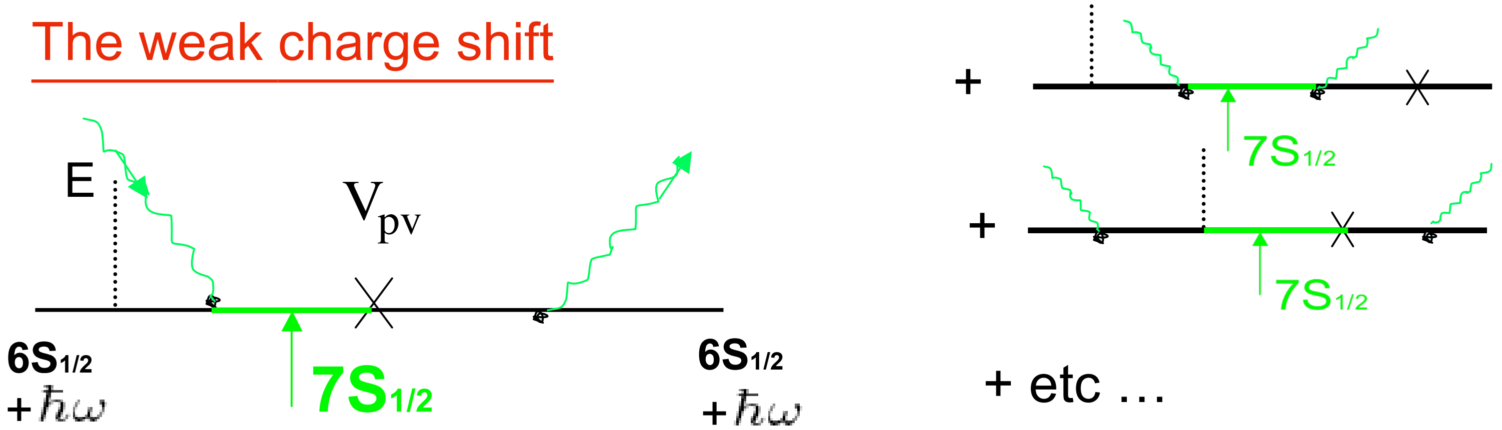
a possible intermediate state provided F’ ≠ F

… but only for the ***nuclear spin dependant*** part

$$< 6S_{1/2}\ F\ |\ V_{ana}\ |\ 6S_{1/2}\ F\pm1 > \neq 0$$

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

The weak charge shift



+ etc …

Is a possible intermediate state ➔ shift enhanced with photons close to the 6S - 7S transition frequency

SUMMARY

- The nS-n’S coupling exerted by the dressing beam transforms

$i\,\mathrm{Im}E_1^{pv}(n,n')\vec{\sigma}$ **a transition electric dipole**

into $\dfrac{\alpha\mathcal{E}^2}{\hbar\delta_F}\,\mathrm{Im}E_1^{pv}\xi\hat{k}\wedge\vec{\sigma}$ **a static one**

both P-odd but T-even

leading to freq. shift

Similarly
the transition
anapole EDM $d_I\ \mathbf{s}\wedge\vec{I}$ **into** $\dfrac{\hbar\Omega^2}{\Delta W\delta}\,d_I\ \xi\mathbf{k}\wedge\vec{I}$ **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:

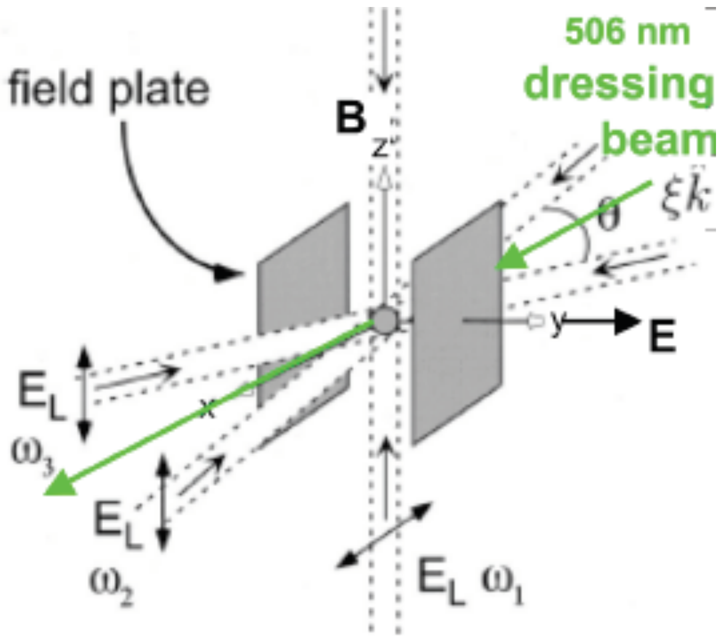
Adjust the dressing beam intensity for acceptable cold atom decay during T_t
& fulfill a compromise between E and dertuning :

Weak charge E ≈ 100 V/cm, $\delta/2\pi \approx$ 65 MHz *from the* **forbidden line**

$\mathcal{E} \approx$ 2.2 kV/cm ➔ $T_t \approx$1 s

Anapole EDM E ≈100 kV/cm, $\delta/2\pi \approx$ 6.6 THz *from the* **resonance line**

Measurement on a sample of cold francium atoms



Weak charge shift expected magnitude
100 μHz in Fr

$N_{at} \approx 10^6$ $\quad$ $^{221}\mathrm{Fr}$ (*I*=5/2) **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

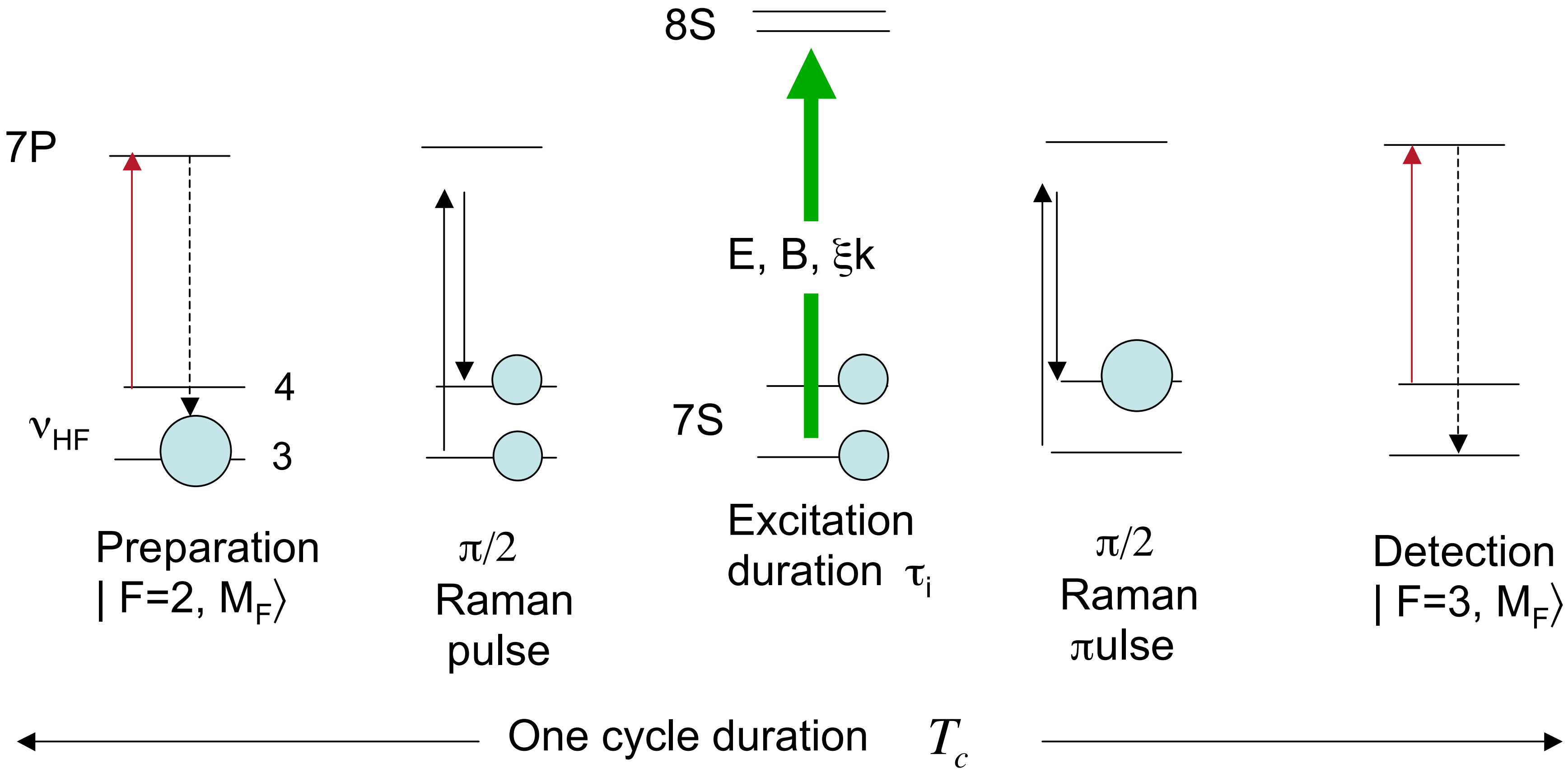
✔ Preparation of a coherent state $(|F,m\rangle + |F',m'\rangle)/\sqrt{2}$ with $F \neq F'$ $m = m'$,
or $F = F'$, $m \neq m'$

✔ Evolution during the interaction time τ_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 .



Preparation
$| F=2, M_F\rangle$

$\pi/2$
Raman
pulse

Excitation
duration τ_i

$\pi/2$
Raman
πulse

Detection
$| F=3, M_F\rangle$

One cycle duration T_c

UNCERTAINTIES

Projection noise and Signal to noise $\propto 1/\sqrt{N_{at}}$ Cold atom number

$$\delta\nu = (1/2\pi\tau_i\sqrt{N_{at}})\sqrt{T_c/\tau}$$

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

τ = total measurement time, $\tau_i \simeq 1$ s

$T_c \approx 2\tau_i$ = duration of one cycle

$$N_{at} = 10^6$$

for Fr

→ S/N = $\Delta\nu^{pv}_{hf}/\delta\nu = \Omega^{pv}\sqrt{\tau/2\Gamma_{n'S}}\sqrt{N_{at}}$ **$\approx$ 30 over one hour**

Independent of E and δ_F (stability condition) and of τ_i (matching $T_c \approx 2\tau_i$)

S/N $\propto \mathcal{E}$ (↗ N_{at} is equivalent to ↘ τ by the same factor)

Signature, Calibration & Syst effects

- Several parameter reversals reduce drifts and syst effects:

  $sign(\delta_F)$ $sign(m_F)$ $sign(\chi = \hat{E} \wedge \xi\hat{k} \cdot \hat{B}$

- Precise calibration is perfomed using the scalar light shift on the forbidden line by modulating the detuning: ± δ_F

  ➔ Ratio $\Delta\nu^{pv}_{hf}/\Delta\nu^{ls}_{hf}$ 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

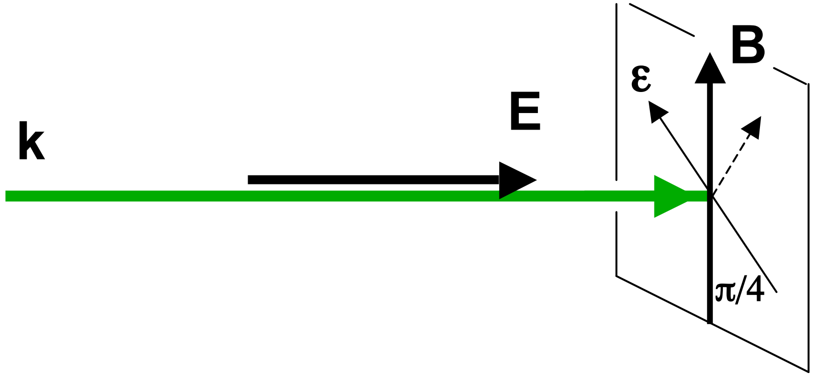
Detuning smaller than the excited state hf splitting $\delta_{FF'} < \frac{\beta}{\alpha} \Delta W(n'S)$

Linear polarization of the dressing beam

➔ **Linear Stark shift** $\propto \vec{\varepsilon}.\,\hat{B}\,(\vec{\varepsilon} \wedge \vec{E}.\,\hat{B})$

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

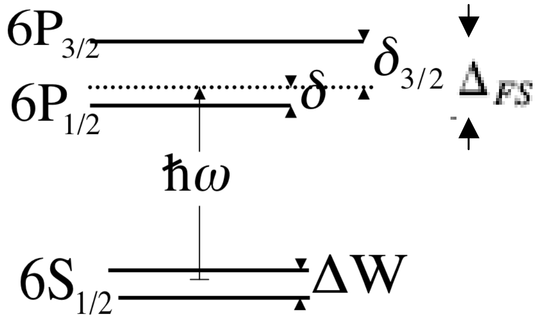
$\vec{E} \perp \vec{\varepsilon}$ **makes the nS-n'S scalar coupling absent**



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

Magnitude of the the anapole shift

$$\frac{d_I E}{\Delta W}\,\frac{\hbar\Omega_1^2}{\delta}$$



Stability condition: not involving the Stark field

$$\Omega_1^2 \le \frac{\delta^2}{\kappa \Gamma_{P_{1/2}} \tau_i} \qquad \delta >> \Delta W$$

➔ advantageous to ↗ δ up to an optimum Δ_{FS} /2.5 ; both P states contribute

In Cs

$E = 100\ \mathrm{kV/cm}$ (big but feasible: H. Gould …) $d_I E/h = 30\ \mathrm{mHz}$

$\delta/2\pi = 6.65\ \mathrm{THz}$

$\Omega_1/2\pi = 2.9\ \mathrm{GHz}$ $B_{ls} = 0.24\ \mathrm{G}$ $B \gtrsim 0.5\ \mathrm{G}$

$\boxed{\Delta\nu^{ana} = 38\ \mu\mathrm{Hz}}$ 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 Ω_1^2 ➔ directly $\frac{d_I E}{\Delta W}$

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 $\langle I \rangle_{trap} = I_{peak}/24$)

- ✔ 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 $\langle I \rangle_{dress}$
  isolated by δ_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 τ_i can be helpful

Atomic P violation experiments at ENS Paris

Brief review in Modern Physics Letters A 20, 6, 375-389 (2005), arXiv:physics/0503143.
J. Guéna, M. Lintz and M.A. Bouchiat. See also Rep. Prog. Phys**. 60**, 1351(1997)

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)
→ **very long preparation work**

« A new Manifestation of Atomic Parity Violation in Cesium: a Chiral Optical Gain induced by linearly polarized 6S-7S Excitation» Phys. Rev. Lett. **90**, 143001 (2003) (J. Guéna, *et al.)*

ABSOLUTE CALIBRATION of E1pv using M1hf

J. Phys. (Paris), **49**, 1851 and 2037 (1988) M.A. and C. Bouchiat, J. Guéna, C.A. Piketty

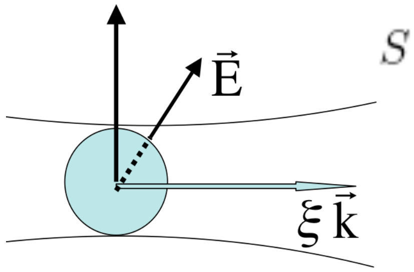
FIRST EXPERIMENTS

Detailed description of the experiment, M.A. Bouchiat, J. Guéna, L. Hunter, L. Pottier
J. Phys. (Paris) **46**, 1897 (1985), **47**, 1175 (1986), **47**, 1709 (1986).
«Observation of a Parity Violation in cesium», M.A. Bouchiat, J. Guéna, L. Hunter, L. Pottier
Phys. Lett **117B,** 358 (1982) & **134B,** 463 (1984) ;

INITIAL WORK

«**Weak Neutral Currents in Atomic Physics**», M.A. Bouchiat & C. Bouchiat,
Phys. Lett **48 B,** 111 (1974); **35**, 899 J. Phys. (Paris), (1974) & **36**, 493 (1975)

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



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

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

$$\mathbf{D}^{ef}(n,n') = -\alpha(n,n')\mathbf{E} - i\,\beta(n,n')\vec{\sigma}\wedge\mathbf{E} - i\,\mathrm{Im}E_1^{pv}(n,n')\vec{\sigma} + M_1\vec{\sigma}\wedge\mathbf{k}$$

$$M_1 \approx 2\times 10^4\,\mathrm{ImE}_1^{\mathrm{pv}}$$

Quantum description of the radiation field

circularly polarized laser beam: $\mathbf{e}(\xi) = \frac{1}{\sqrt{2}}(\mathbf{e}_1 + i\,\xi\,\mathbf{e}_2)$

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

$|\tilde{i}\rangle = |n\,\widetilde{S_{1/2}}\rangle\,|N\rangle$ and $|\tilde{f}\rangle = |n'\,\widetilde{S_{1/2}}\rangle\,|N-1\rangle$

Combined atom-field eigen states

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

Calculation of the shift by time-independent perturbation theory

Special tools for taking up the challenge

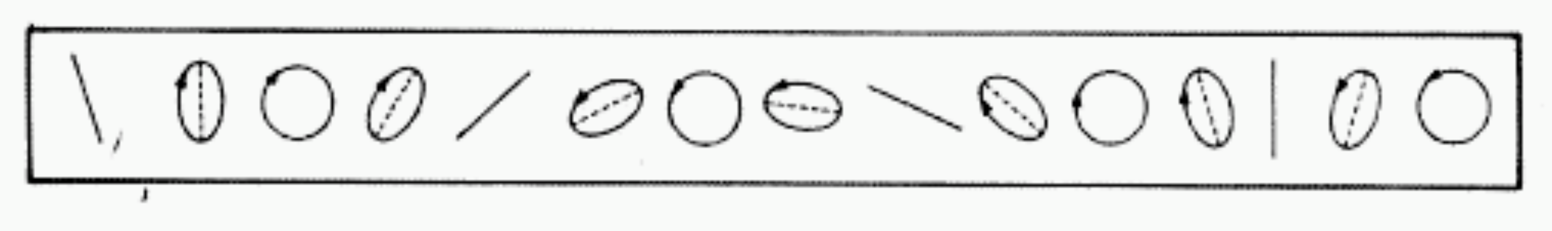
✔ Intense **tunable laser** at 539 nm (with a narrow spectral width)

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