Interférométrie atomique et structure du noyau

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Introduction: quelques rappels

- Violation de P : un effet très grand dans les noyaux
- ….infime dans les atomes. Pourquoi?
- Comment la détecte-t'-on dans les atomes?
- Cas de la transition 6*S*-7*S* césium

Etat présent de ce domaine. Buts actuellement poursuivis

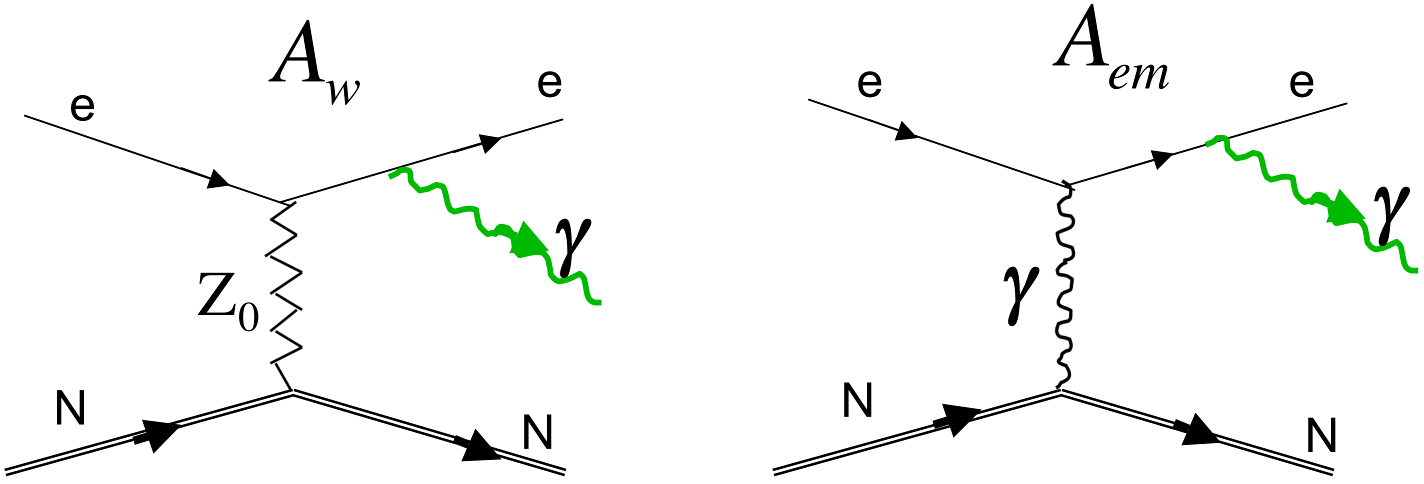
- charge faible et moment anapolaire
- motivation pour **une nouvelle stratégie** et en particulier
- **les déplacements de fréquences atomiques**
- **dans un état atomique stationnaire habillé par une onde laser**

Revue de candidats possibles

- Deux types de déplacements:
- Donne accès **soit** à la charge faible **soit** au moment anapolaire
- **Signature, grandeur et contraintes expérimentales**

Conclusion : **nouvelles perspectives**

In atoms L-R PV-asymmetries are exceedingly small 10^{-6} **WHY ?**



Z_0 exchange competes with photon exchange

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

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

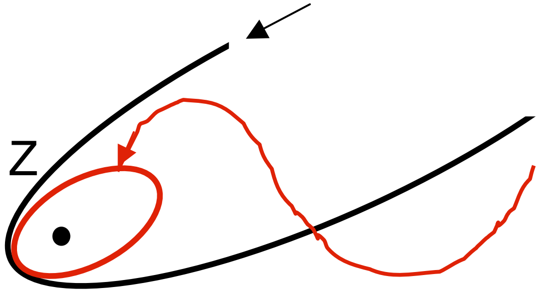
nothing similar in ß-decay : $Asym \approx A_w^{odd} / A_w^{even}$

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

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

But there are enhancement effects!

First enhancement effect: the Z^3 Law (M-A Bouchiat & C. Bouchiat 1974)



Penetrating orbital

Nucleus of charge Z

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

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

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

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

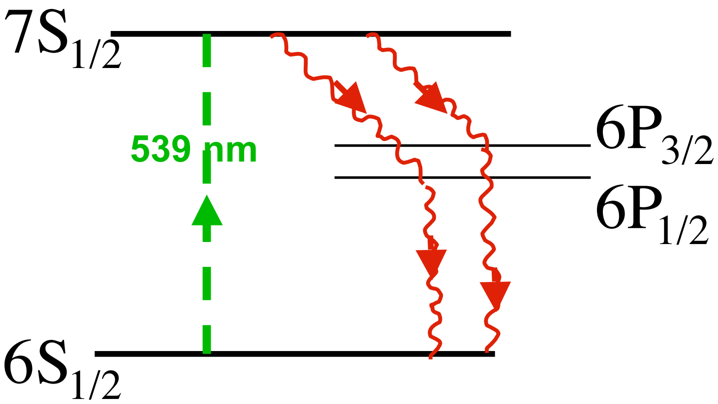
Even faster than Z^3 because of relativistic effects

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 Z_0 exchange breaks the Parity selection rule

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

M_1 is allowed by symmetry

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

$$\approx 2 \times 10^{4} \times i\, E_1^{pv}$$

M_1 Transition rate 10^{-6}/s➔ one photon per 10 days !

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

The $6S_{1/2} \rightarrow 7S_{1/2}$ Stark induced transition

P states are admixed to S states There is a new transition dipole :

$$\vec{d}^{\,ind} = \alpha\, \vec{E} + i\, \beta\, \vec{\sigma} \times \vec{E}$$

(10 times smaller)

Scalar and vector polarizability of the transition

Parity conserving Induced electric dipole amplitude: $E_1^{ind} = \vec{d}^{\,ind} \,.\, \mathcal{E}\, \vec{\varepsilon}$

We have excellent control of E_1^{ind} by adjusting :

the field in magnitude and direction

& the polarization

$E_1^{ind} E_1^{pv}$ is the type of interference effect detected in all PV exp. so far

Asymmetry in the transition rate: $Asym_{L\text{-}R} = 2\, E_1^{ind} E_1^{pv} \,/\, \left|E_1^{ind}\right|^2$

a few 10^{-6}

The effective dipole operator for the forbidden transition and the calibration of E_1^{pv}

$$\vec{D}_{eff} = -\alpha\,\vec{E} - i\,\beta\,\vec{\sigma}\times\vec{E} + M_1\,\vec{\sigma}\times\vec{k} - E_1^{pv}\,\vec{\sigma}$$

Each term is an operator in the spin space

coefficients are matrix elements calculated in the atomic radial coordinate space

Four contributions ➔ many interference effects which can be used for controls and for calibration.

Absolute calibration of E_1^{pv} is possible (within a precision better than 10^{-3})

The amplitude of reference is a contribution to M_1 (so called M_1^{hf}) ,
precisely known theoretically
which arises from hyperfine mixing between the two S states

One can isolate $M_1^{hf} E_1^{ind}$ and compare to $E_1^{pv}\ E_1^{ind}$

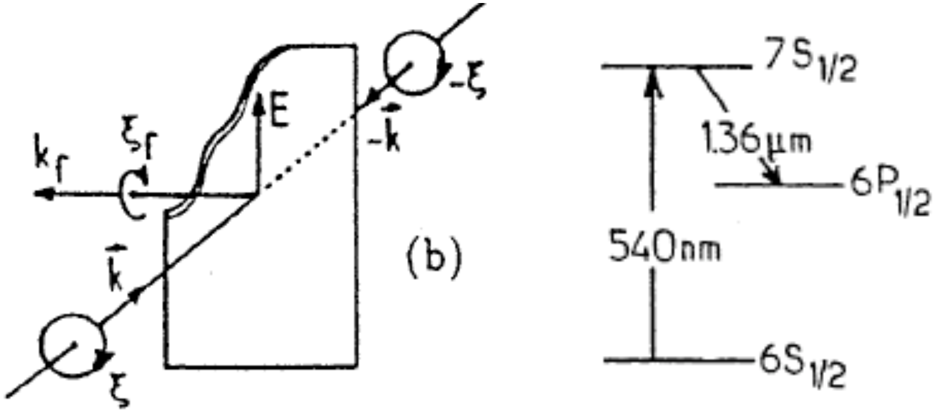
Manifestations of Parity Violation in Atoms

for resonant excitation of the 6S-7S Cs transition

Paris 1982

Symmetry breaking of the atomic fluorescence

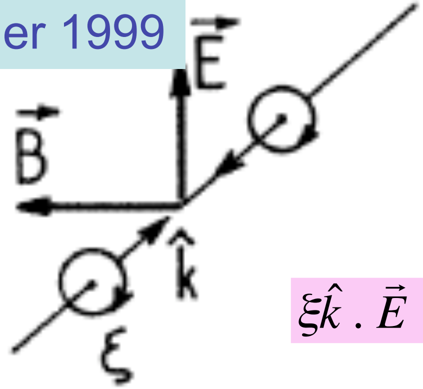
$\xi\hat{k}\,.\,\vec{E}\times\xi_f\hat{k}_f$



Phys. Lett., **117B**, 358 (1982) & **134B**, 463 (1984)

Chiral absorption in crossed E&B fields

Boulder 1999



$\xi\hat{k}\,.\,\vec{E}\times\vec{B}$

C. Wood, et al. , Science, **275**, 1759 1999)

Asymmetry in the transition rates

a few 10^{-6}

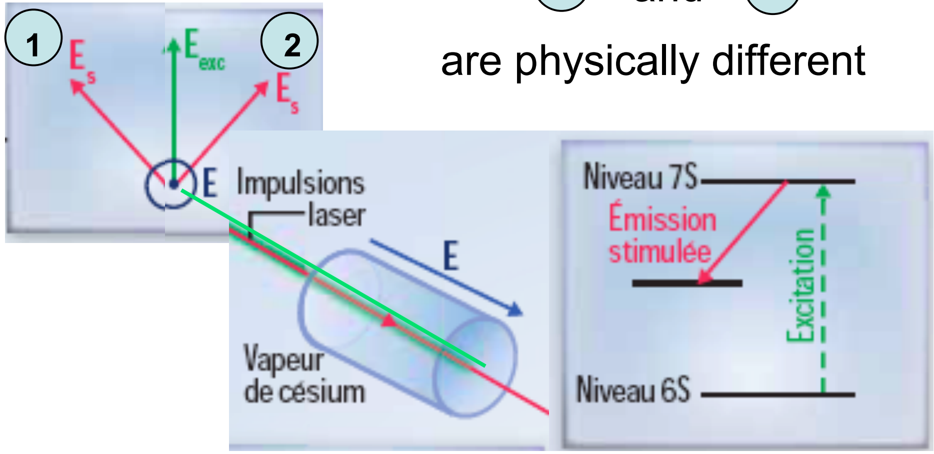
Paris 2005

$(\vec{E}_{exc}\,.\,\vec{E}_s)(\vec{E}_{exc}\,.\,\vec{E}\times\vec{E}_s)$

Chiral optical gain detected on the amplified probe beam

① and ②

are physically different

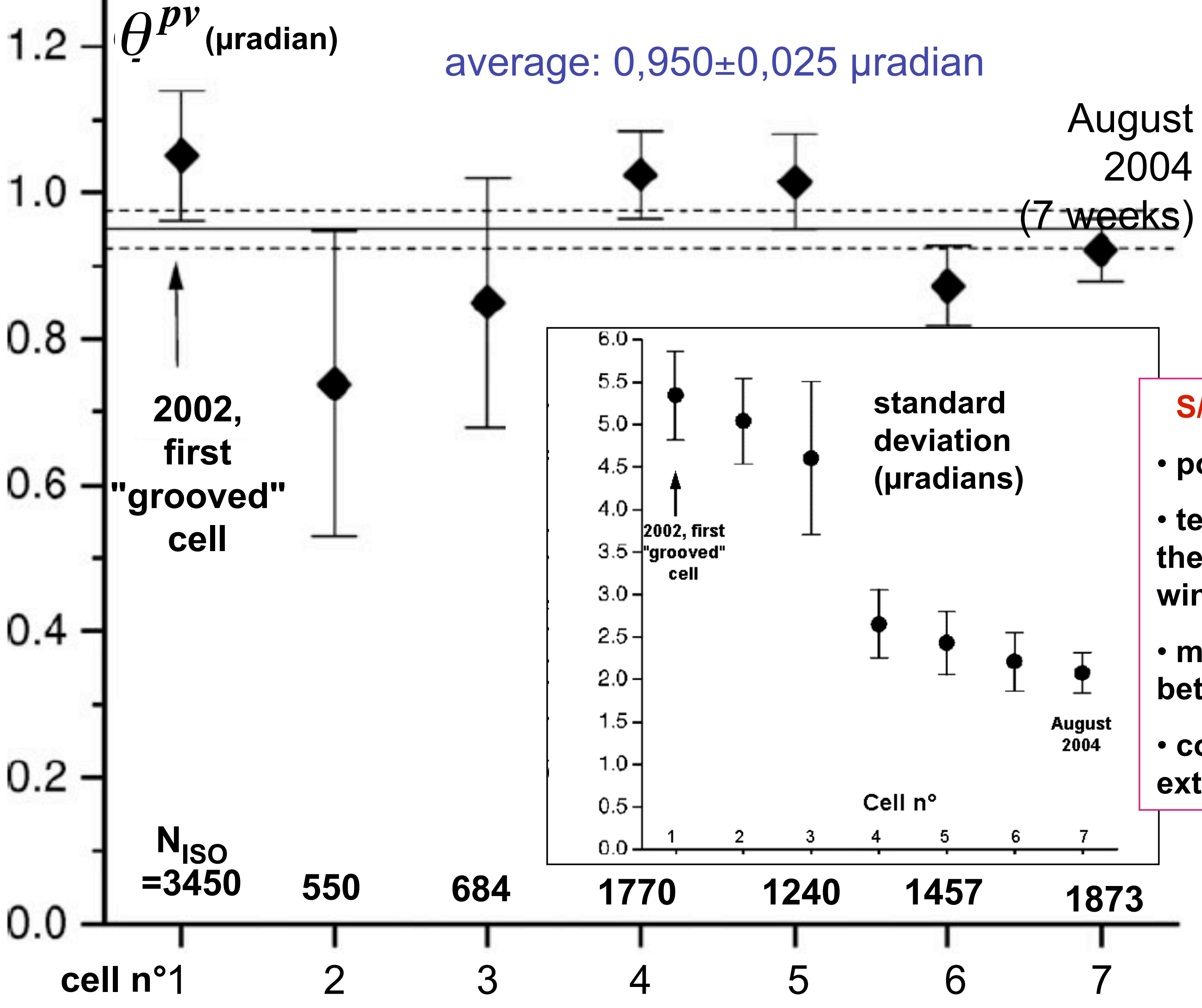


J.Guéna, M.Lintz & M.A.B, PRA **71**, 042108 (2005)

Chiral optical gain measurement (Paris 2004)

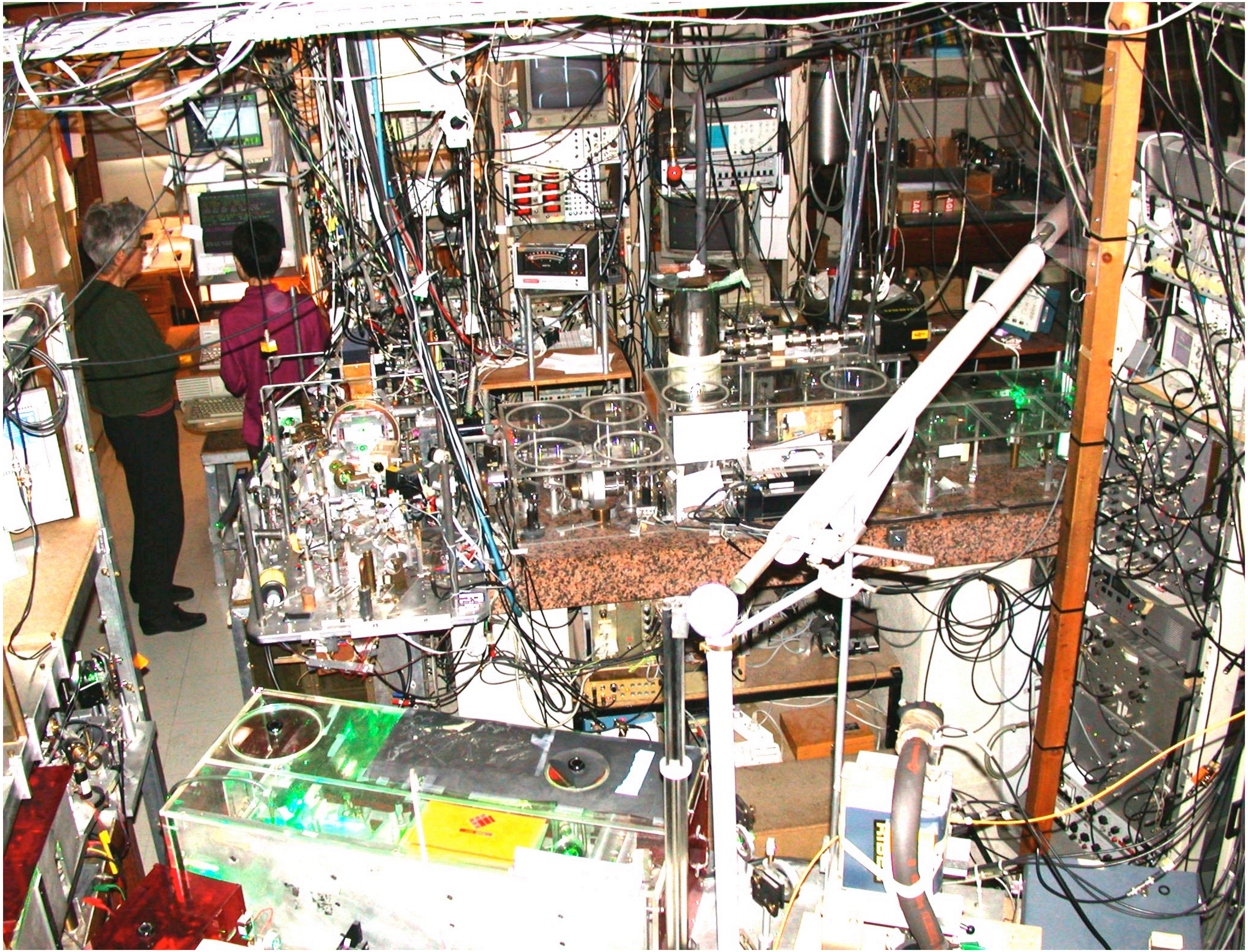
➔ E_1^{pv} with an absolute accuracy of 2×10^{-13} atomic units (ea0)

J.Guéna, M.Lintz & M.A.B, PRA **71**, 042108 (2005)

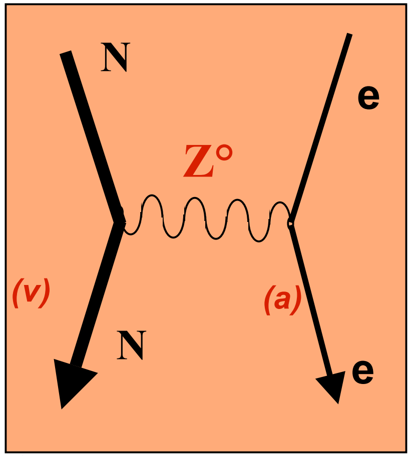


S/N improved by use of

- polarization tilt magnifier
- temperature control of the reflection at the windows
- metal-coated windows for better application of E_z field
- control of the probe gate extinction factor



What is measured in Atomic Parity Violation experiments ?



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

between the nucleus and electrons

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

➔ The weak charge Q_w $in\ V_{pv}$ plays the same role as the electric charge $in\ V_{em}$

➔ **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

dependance on the hyperfine transition

The consequence of APV: forbidden transitions … …are not strictly forbidden

Weak charge

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

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

Fermi constant
very well known

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

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

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

$$E_1^{pv} = \underset{\approx\ -N}{Q_W} \times \text{atomic factor}$$

atomic factor → **known from theory**

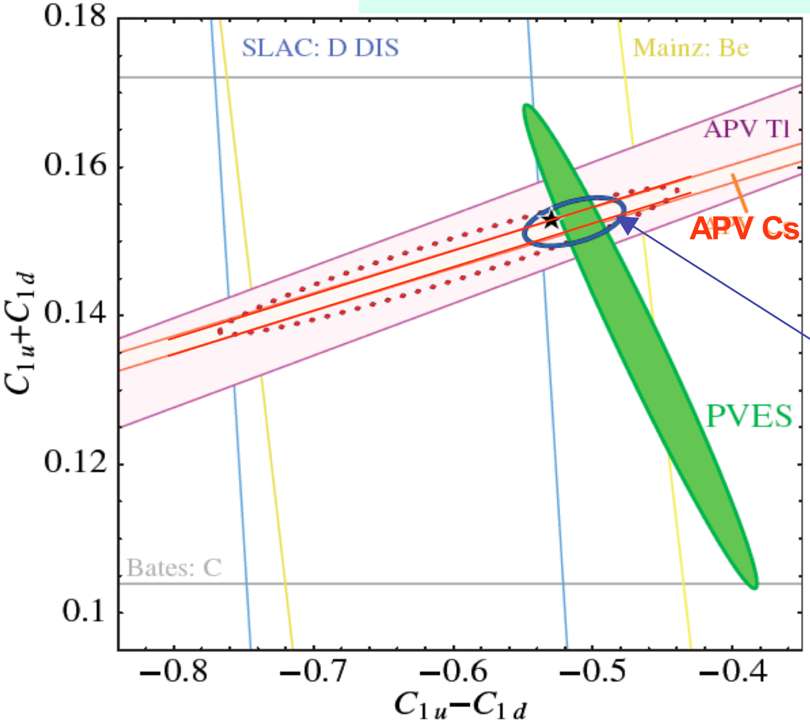
$Q_W \approx -N$ → **to be determined**

Cs: the APV transition dipole moment is accessible (Z^3 law + relativ. effetcs)

calculations have reached the 0.27% accuracy level (and should be improved to 0.15%)

➔ **Cs = best choice among the stable alkalis:**

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 (1SD)

Boulder 1999

Polarized Electron Scattering (1SD)

Full constraint 95% CL

* Standard Model prediction

Constraints on the weak charges of the u and d quarks

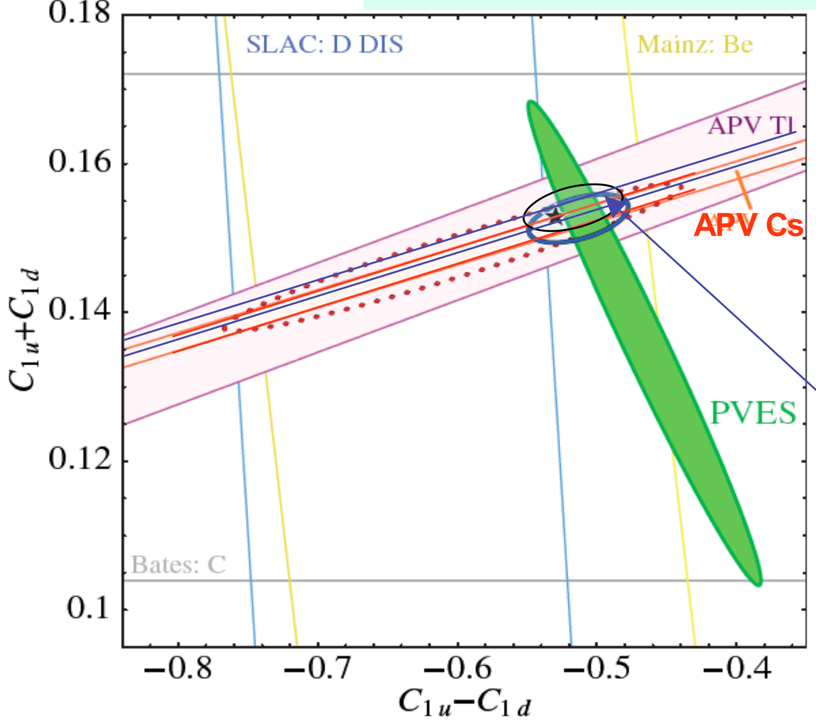
$$Q_w^A = -2\left[(2Z+N)C_{1u} + (Z+2N)C_{1d}\right] \qquad \text{from APV}$$

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

in the forward scattering limit

Limits on an additional weak boson Z’ Mass: **M(Z’) >1.7 TeV/** c^2
predicted by supersymmetric extensions of the SM
(supposing gauge couplings to matter-fields kept unchanged)

The weak charge: New Atomic Theory results 2009



S.G. Porsev, K. Beloy, A. Derevianko, arXiv09020333

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

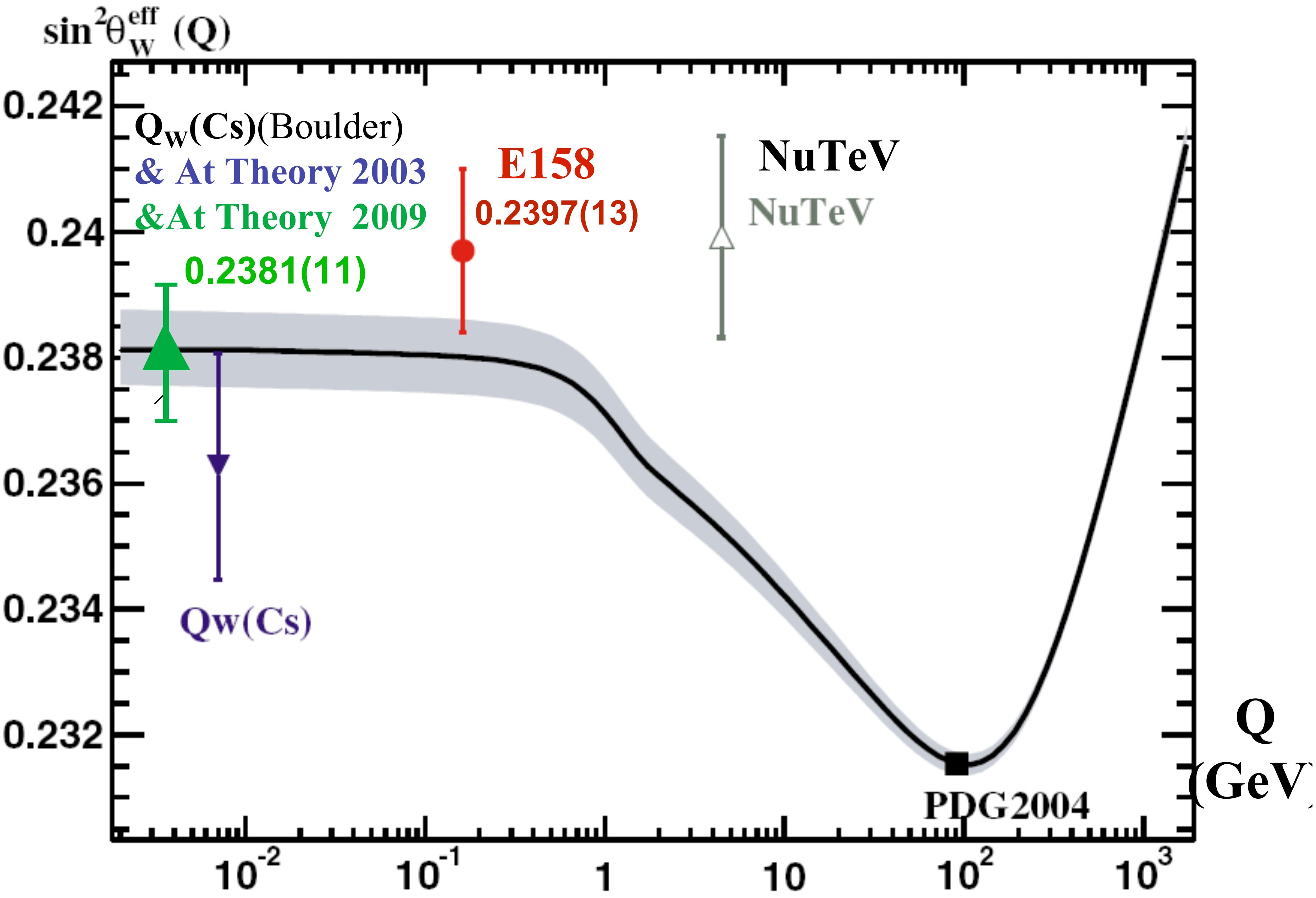
* Standard Model prediction

✔ Compared to the direct search of the Z’ gauge boson searched at Tevatron collider yielding $M > 0.82\ \mathrm{TeV}/c^2$ this new result implies $M > 1.3\ \mathrm{TeV}/c^2$ (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

SLAC E158 coll. (PRL, 2005)



The neutron skin and Isotope Effects

rms distribution radii

$$\frac{\delta E_1^{pv}}{E_1^{pv}} = \underbrace{-\frac{3}{7}(Z\alpha)^2}_{0.069} \underbrace{\frac{R_n - R_p}{R_p}}_{\Delta R_{np}/R_p}$$

$\Delta R_{np}/R_p$? $\delta E_1^{pv}/E_1^{pv}$

✔ Nuclear mean field theory **0.016 to 0.022** depending on the nuclear force model **-0.0013 (3)**

✔ Recent empirical information from antiproton Expts at Lear (**PRL 87, 082501 (2001)**)
for many stable atoms but not Cs
➔Global fit of the data. Assuming its validity for Cs ➔ **0.027 (8)** **- 0.0019 (6)**

✔ Reanalysis of the antiproton data using Skyrme models ➔ 0.033 (7) **-0.0023 (5)**
(A. Derevianko arXiv.0804.4315 hep-phys)

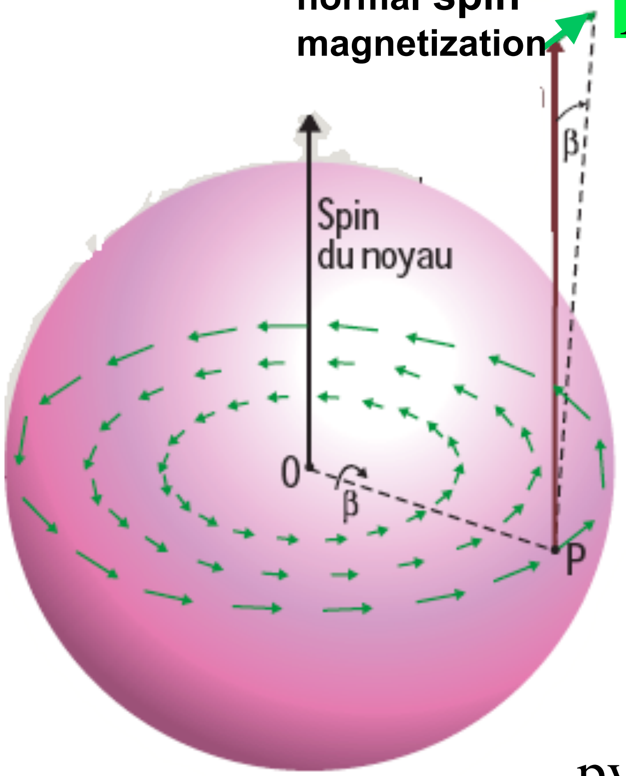
Uncertainty introduced in a single isotope measurement is small: **in Cs less than 0.1%**

Effects are larger in Fr : 0.0062(16) for $^{223}\mathrm{Fr}$

Measurements made on several isotopes ➔neutron skin information

Complementary approach to the proposed Lead Radius Experiment on $^{208}\mathrm{Pb}$ JLab

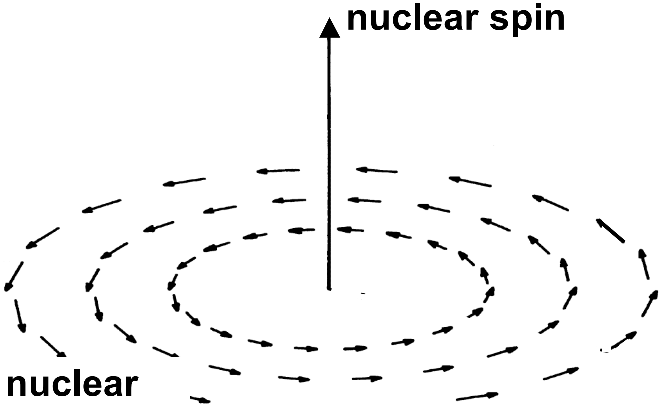
The nuclear anapole moment a qualitative description



normal spin magnetization

M^{pv}

P-violating **nuclear spin magnetization**



nuclear spin

P-violating **nuclear spin magnetization**

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

a vector

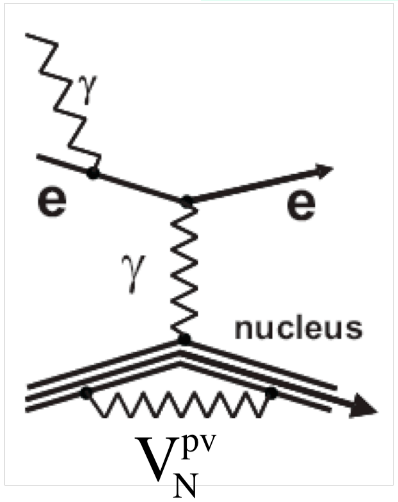
$$\vec{a} = 2\pi \int d^3r \;\; \vec{r} \times \vec{M}^{pv}(r)$$

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 unperturbed nuclear 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)

Nuclear-spin dependent PV interaction

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 : $\dfrac{\mathrm{E_1^{pv}(6S,F=4 \rightarrow 7S,F=3)}}{\mathrm{E_1^{pv}(6S,F=4 \rightarrow 7S,F=4)}} = 1+\eta$ **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 !

Present Goals for Atomic Physics experiments

- **Measure Q_w to 0.1% precision in Cesium** in view of the expected gain of precision
  in atomic structure calculations and in order to cross-check the Boulder result.

- **Devise feasible expts on francium (Z=87)** where the PV effect is 20 times larger
  but atoms are radioactive and scarce

- **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

Present Projects

- **Yb** at Berkeley (D. Budker)
- **Ba+** at Seattle (N. Fortson) ➔ Groningen (K. Jungmann et al.) and **Ra+** (Groningen)
- **Fr** at TRIUMF (large collab using the know how of the Stony Brook group)
  and pioneering work at Legnaro by Italian groups.

Can we find new strategies for APV measurements?

Up to now expts in forbidden transitions have been based upon Left-Right asymmetries in the transition rates (polarization-dependent). Have we reached their limit of precision ?
A proposal: J. Guéna, M; Lintz & M.A. Bouchiat J. Opt. Soc. B 21, 22 (2005), requires large atomic densities.

By contrast frequency measurements on cold atoms & trapped ions have demonstrated high, rapidly improving, accuracies & can be adapted to small samples of atoms

e.g.: fractional accuracy of atomic Cs clocks 10^{-16}, limit on the e-EDM, …

e-EDM present limit $1.6\times10^{-27}\,\mathrm{e}\times\mathrm{cm}$

Thanks to a

record of sensitivity in Tl: $2\times10^{-16}\,\mathrm{ea}_0$

achieved sensitivity in Cs d(6S-7S): $3\times10^{-14}\,\mathrm{ea}_0$

0.1% **goal** $8\times10^{-15}\,\mathrm{ea}_0$

0.1% **goal in Fr d(7S-8S):** $1.6\times10^{-13}\,\mathrm{ea}_0$

Why is it far behind ?

There is no linear Stark shift associated with a transition electric 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)

New approaches relying on light-shifts

– A concrete proposal➔ Exp on the Ba+ ion N. Fortson, Phys. Rev. Lett. **70**, 2383 (1993)

$6S_{1/2} - 5D_{3/2}$ transition

under way with two standing waves, one driving E_2, the other the E_{1pv} amplitude

(One single ion precisely located at a node of one wave and antinode of the other wave

Can the optical fields and phases be stabilized enough?)

New light shifts

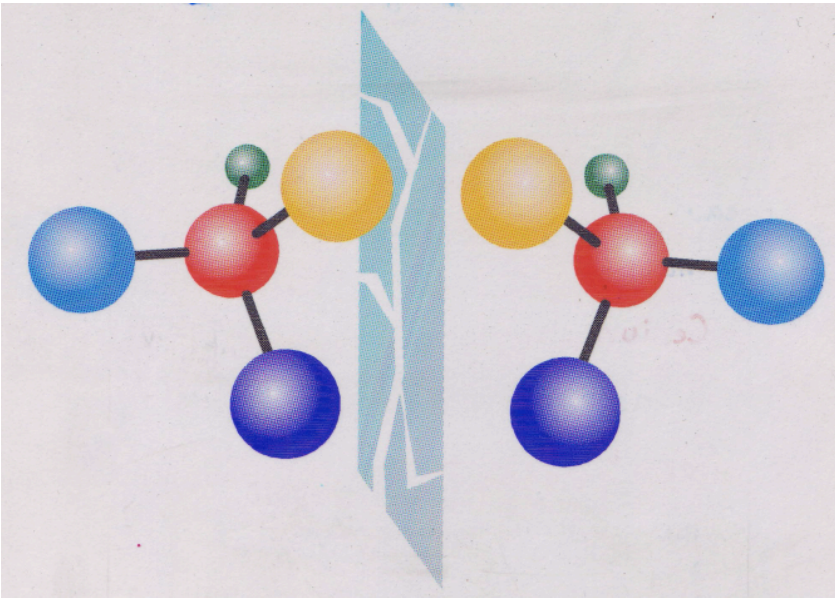
Here we look for new light-shifts with suggestions of realization

with no needs for trapped ions

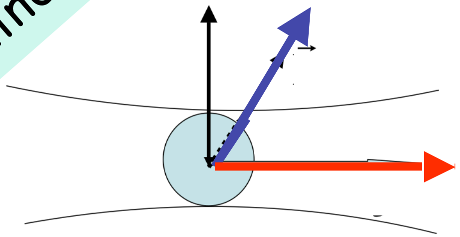
which apply to many atoms if you can get them

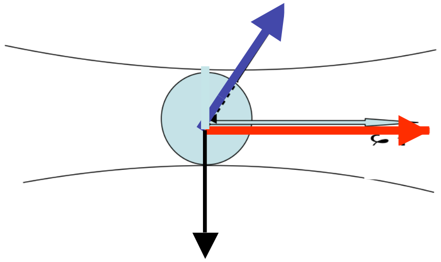
Another idea : make Cs atoms behave similarly to enantiomer molecules ?

If the chirality of the chemical site inside an enantiomer is replaced
by the chirality of a certain field configuration …much easier to control & to compute!
two mirror-image configurations would give shifts of opposite signs.



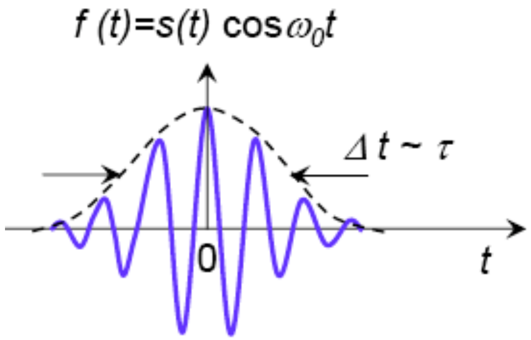
To be defined !

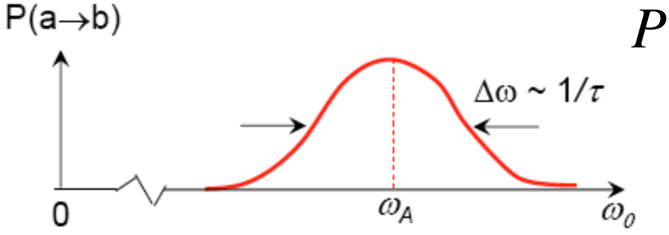




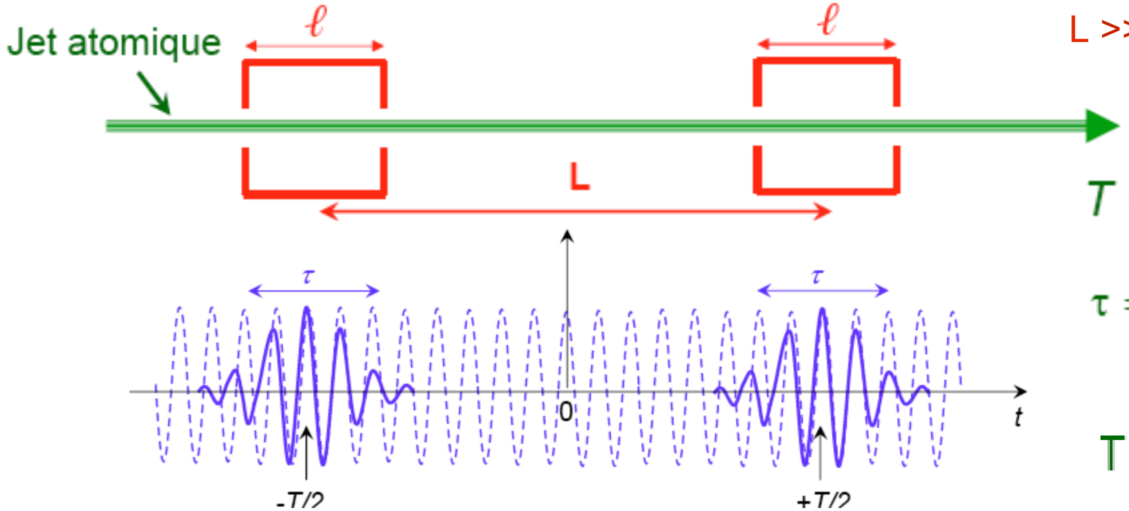
This is our goal : transfer APV asymmetry measurements from transition-probability to frequency-shift domain

Transition probability induced by an EM oscillating field





$$P(\omega) = \left| \boldsymbol{F}(f(t)) \right|^2$$



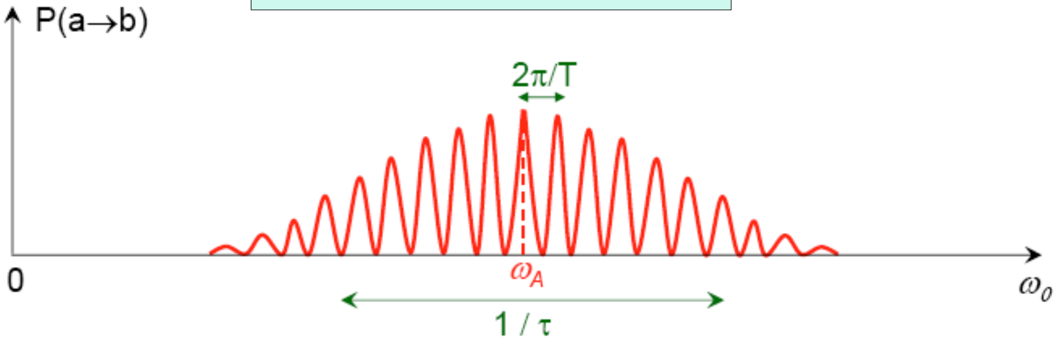
$L >> \ell$

$T = L / v$

$\tau = \ell / v$

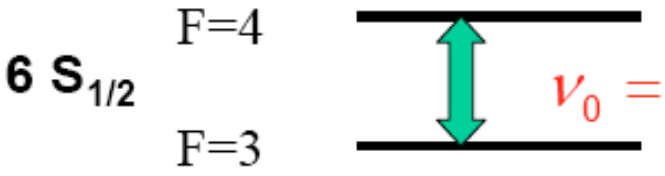
$T >> \tau$

Ramsey Fringes



Atomic clocks are oscillators having their frequency locked on a **universal reference** :
the frequency of an atomic transition

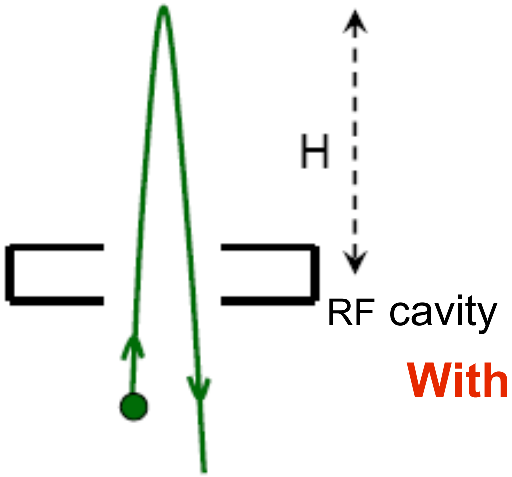
Definition of the unit of time : from the number of oscillation periods in one second



$\nu_0 = 9\,192\,631\,770$ **Hz** $\quad {}^{133}\mathrm{Cs}$

Atomic clocks using ultra-cold atoms

High precision requires narrow lines



Cold atoms launched by a laser pulse only feel the gravity field and cross the cavity twice

$$g(T/2)^2/2 = H \quad \rightarrow \quad T = 2\sqrt{2H/g}$$

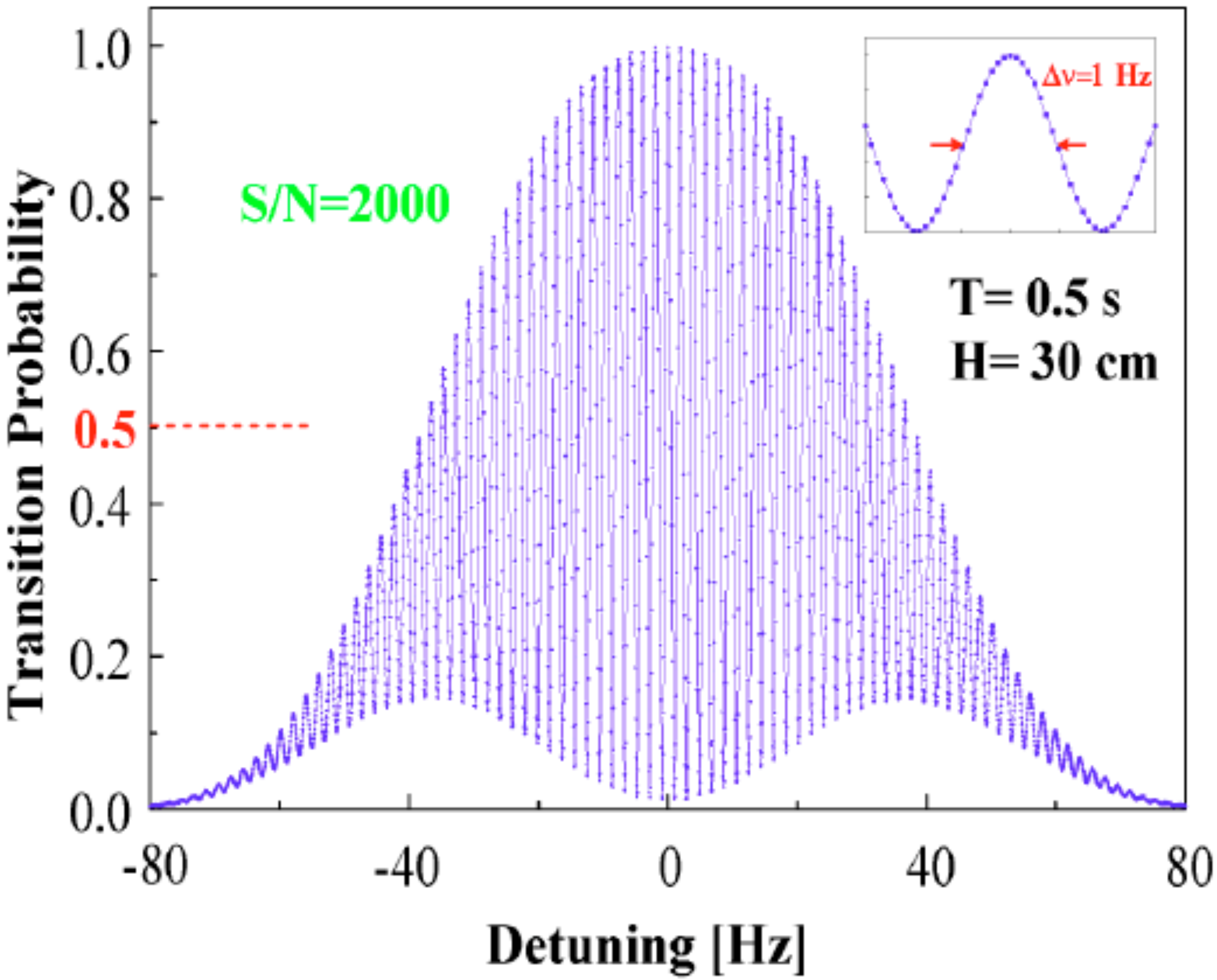
$H = 50$ cm $\rightarrow$ $T = 0.6$ s

With respect to traditional clocks the gain is by 200

Achieved frequency stability 1.6×10^{-16} for an integration time of 5×10^{4} s

Exactitude 3×10^{-16}

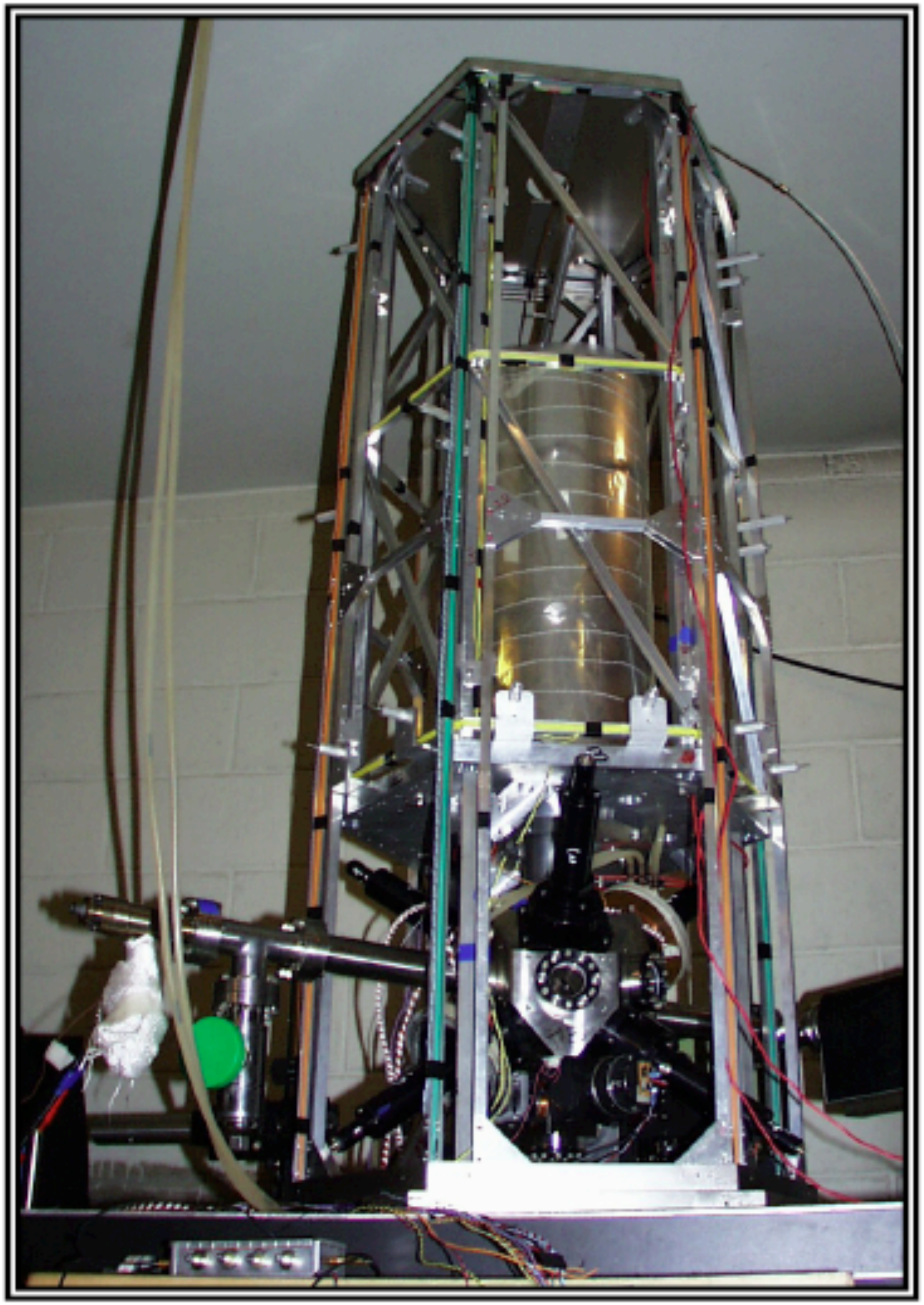
Ramsey Fringes in an atomic fountain



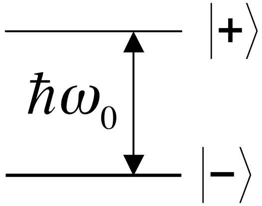
G. Santarelli et al., Phys. Rev. Lett. 82, 4619 (1999)

Fontaine atomique du BNM-LPTF

A. Clairon, C. Salomon, et al.



Quantum description of a spin 1/2 during a Ramsey cycle



A two-level system, with energy difference $\hbar\omega_0$
Is represented by a fictitious spin 1/2
placed in the magnetic field $\vec{B} = B_0\,\hat{z} + \vec{B}_1$

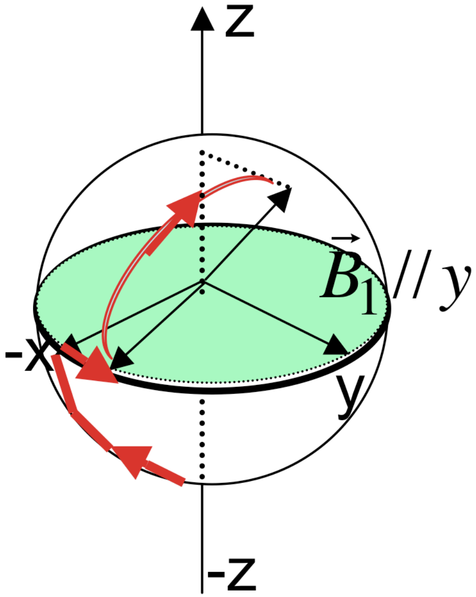
$$B_0 = -\hbar\omega_0/\mu_0 \quad B_1 = -\hbar\Omega_R/\mu_0 \quad \vec{B}_1 = B_1(-\hat{x}\,\sin\omega t + \hat{y}\,\cos\omega t)$$

$\vec{B}_1$ applied only during two short pulses $t_{\pi/2} = \pi/2\Omega_R$, assuming $\Omega_R >> \omega_0 - \omega$

$\mu_0 < \vec{S} >$ **evolves exactly as a classical magnetic moment**

Evolution of the spin in the rotating frame : $\vec{B}_1$ is fixed but there is an extra field //z nearly opposed to B₀

➔ effective field $B_{eff} = -\hbar(\omega_0 - \omega)/\mu_0$



$\vec{S}$ initially //-z
1rst pulse: rotation of $\pi/2$ around $\vec{B}_1$
For T>> $t_{\pi/2}$ with $\vec{B}_1$ off, precession of $(\omega_0 - \omega)T$ around z
2nd pulse: rotation of $\pi/2$ around $\vec{B}_1$
Detection: polarization along z

$$P_\pm = \frac{N_\pm}{N_+ + N_-} \qquad P_\pm = \frac{1}{2}(1 \pm \cos(\omega_0 - \omega)T)$$

$$\psi(t_{\pi/2}) = \frac{1}{\sqrt{2}}\left(|+\rangle + |-\rangle\right) \Rightarrow \psi(T + t_{\pi/2}) = \frac{1}{\sqrt{2}}\left(|+\rangle + exp(i\varphi)\,|-\rangle\right)$$

Is it possible to circumvent the rule

which interdicts any Stark shift

for an electric dipole of transition

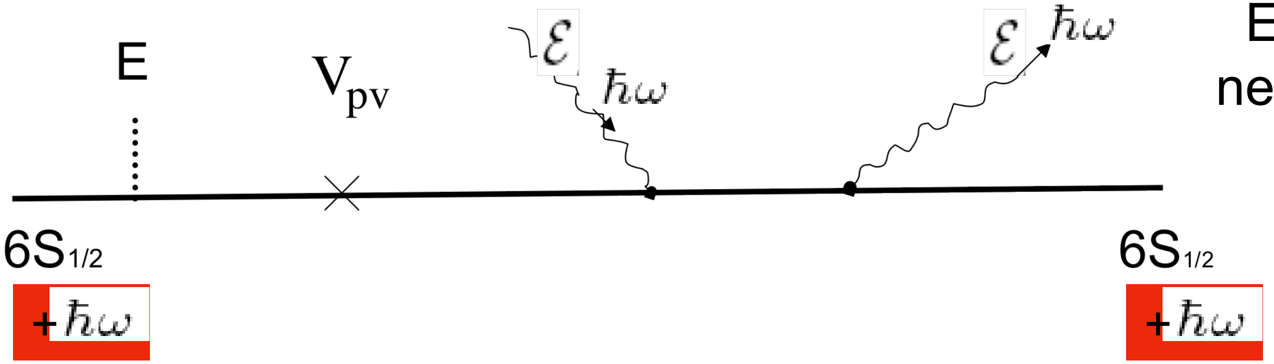
By applying a radiation field

??

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

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

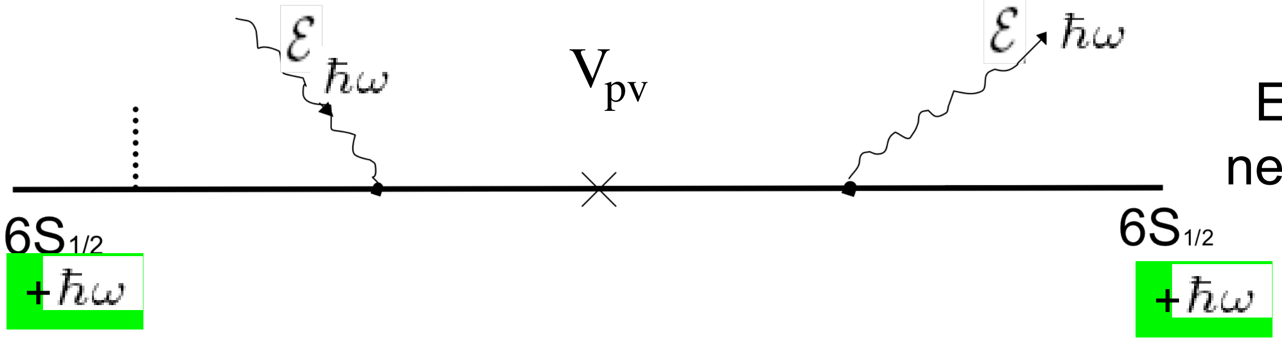
Time ordered diagrams:



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

V_{pv}^{NSD}

Anapole moment



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

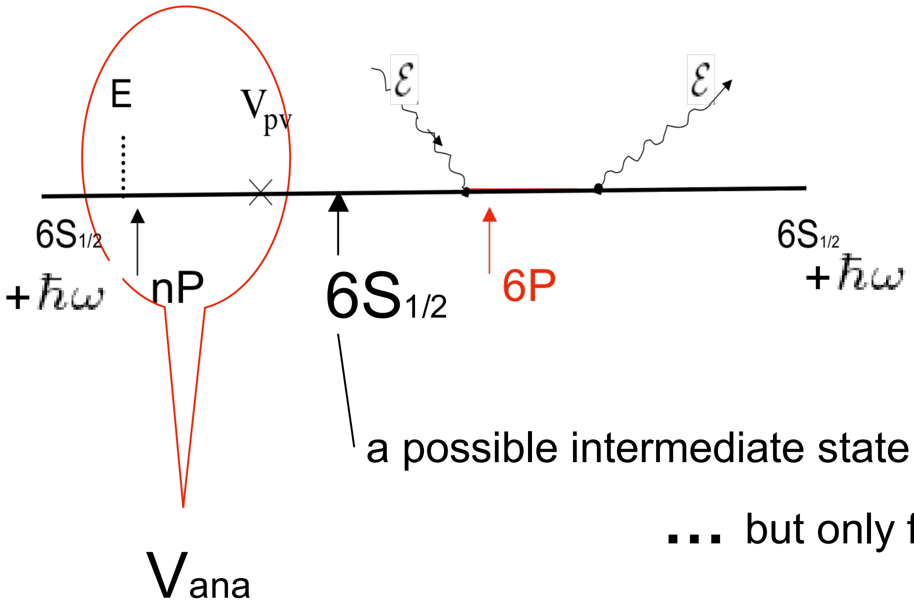
V_{pv}^{NSI}

Weak nuclear charge

+ … permutated order + h. c.

Two kinds of shifts

- ## The anapole shift



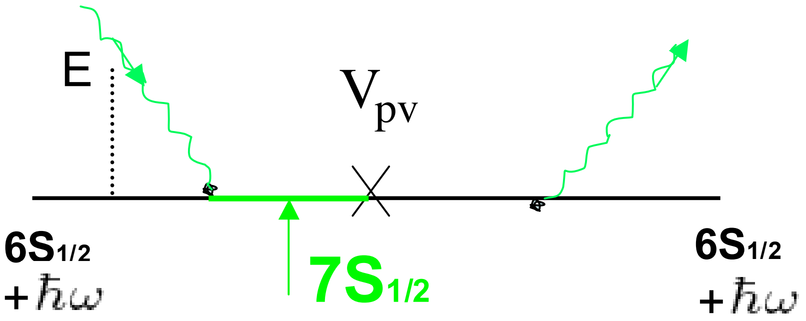
a possible intermediate state provided $F' \neq F$

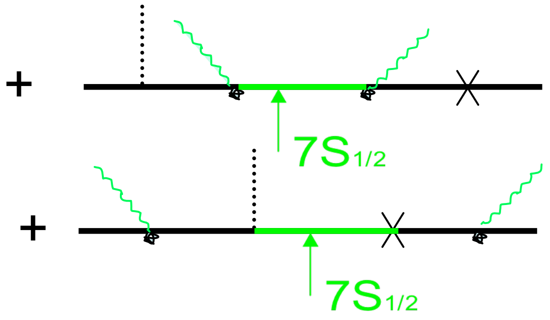
… but only for the ***nuclear spin dependant*** part

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

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

- ## The weak charge shift



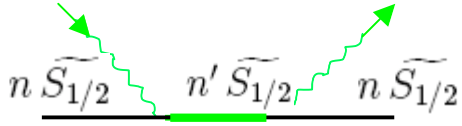


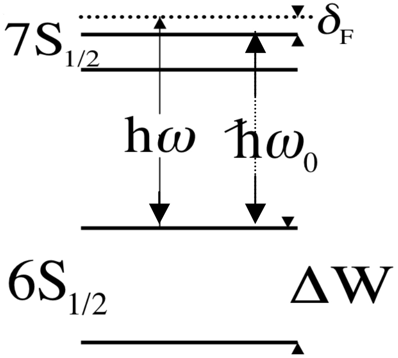
+ etc …

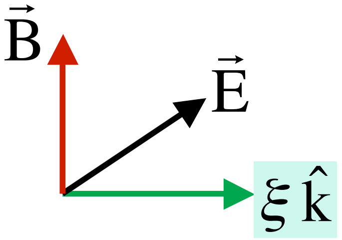
Is a possible intermediate state ➔ shift enhanced with photons close to the
6S - 7S transition frequency

Qw shift: nS-n'S near-resonant circularly-polarized beam

Virtual radiative transition between the perturbed states







photon angular momentum

$$\delta E_{F,m_F} = \sum_{F',m'_F} |\langle n\widetilde{S_{1/2}}; F m_F | V^{ef}_{rad} | n'\widetilde{S_{1/2}}; F'm'_F\rangle|^2/\hbar\delta$$

$$\delta = \omega - \omega_0$$

$$\mathcal{E}\,\hat{e}(\xi).\vec{D}_{ef}$$

$$\hat{e}(\xi) = (\hat{E} + i\,\xi\,\hat{k}\times\hat{E})/\sqrt{2}$$

$$\hat{e}(\xi).\vec{D}^{ef} = \alpha\vec{E}.\hat{e}(\xi) + i\ \mathrm{Im}\ E_1^{pv}\vec{\sigma}.\hat{e}(\xi) + \ldots$$

Rabi frequencies

$$\Omega^{\alpha}_{ind} = \alpha E\mathcal{E}/\hbar\sqrt{2}$$

$$\Omega_{pv} = \mathrm{Im}E_1^{pv}\mathcal{E}/\hbar\sqrt{2}$$

$$\delta E_{F,m_F} = 2\,\frac{\hbar\Omega^{\alpha}_{ind}\,\Omega_{pv}}{\delta_F}\langle F,m_F|\,\vec{E}\,.\,\xi\,\hat{k}\times\vec{\sigma}\,|F,m_F\rangle \equiv \vec{D}_{pv}\,.\,\vec{E}$$

δ_F for the $\Delta F = 0$ transition

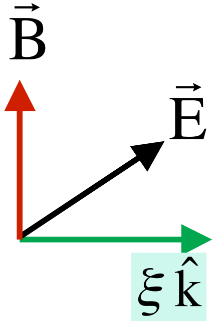
Linear Stark shift

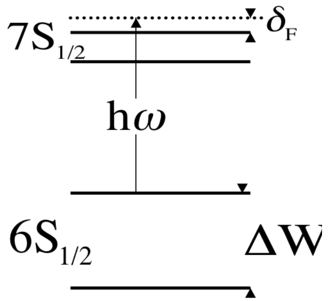
Static dipole P-violating, T-preserving:

$$\mathbf{D}_{pv} = \boxed{\frac{\alpha\mathcal{E}^2}{\hbar\delta_F}\,\mathrm{Im}E_1^{pv}\xi\hat{k}\wedge\vec{\sigma}}$$

The weak charge shift : result

If **B, applied along** $E\wedge\xi\hat{k}$**,** is the quantization axis



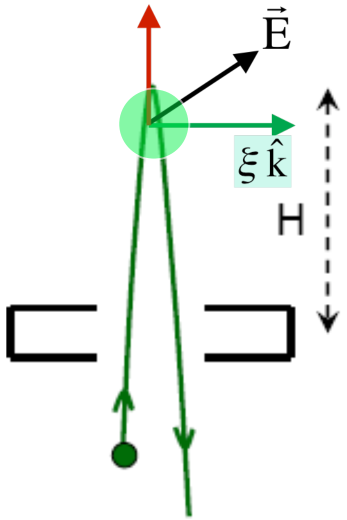


Linear Stark shift of a $|F,m_F\rangle$ state

$$\delta E_{F,m_F} = 2\,\frac{\hbar\Omega^{\alpha}_{ind}(\Omega_{M_1}+\xi\Omega_{pv})}{\delta_F}\,\frac{m_F}{I+1/2}\;\hat{E}\wedge\xi\hat{k}\cdot\hat{B}$$

odd under reversal of the chirality of the configuration

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



➔ A shift of hyperfine and Zeeman transition frequencies ☺

within reach, see below

CAUTION **!!**

1) the dressing beam can ionize the atoms
2) it makes the ground state unstable
3) It produces a fictitious magnetic field $B_{ls}\propto\xi\,\hat{k}$

Minor or serious problems ?

Minor or serious problems ?

1) Two-photon photoionization rate by the dressing beam for francium at 506 nm

R $\propto$ (photon flux)^2 = 4×10^{-5} s for $\mathcal{E}$ = 2.2 kV/cm

From H.B. Bebb (1966) QDT

10kW/cm^2

$\mathrm{Im}E_1^{pv}$ From V.V. Flambaum, Phys. Rep. **397**, 63 (2004) ➔ $\Omega^{pv}/2\pi \simeq 0.30$ Hz

2) Ground state decay rate resulting from nS-n'S coupling

$$\Gamma_{nS_F} = \Gamma_{n'S}(\Omega^{\alpha}_{ind}/\delta_F)^2$$

We want $\Gamma_{nS_F}\tau_i \leq 1$ for a typical interaction time of 1s

$$\boxed{\Rightarrow |\Omega^{\alpha}_{ind}/\delta_F| \leq (\Gamma_{n'S}\,\tau_i)^{-1/2} \equiv 2.5\times10^{-4}/\sqrt{\tau_i(s)}}$$

Large range 20 < E (V/cm) < 1 000

13 < δ_F (MHz) < 650

This completes the determination of the pv Stark shift:

$$\delta E^{pv}_{F,m_F} = sign(\delta_F)\,(\Gamma_{n'S}\tau_i)^{-1/2}\,\hbar\Omega^{pv}\frac{2m_F}{I+1/2}\;\hat{E}\wedge\xi\hat{k}\cdot\hat{B}$$

MA Bouchiat
arXiv :0711.0337 physics
PRL **100**, 123003 (2008)

➔ **0.1 mHz** for francium, *m*=*I*-1/2

20 times less for cesium

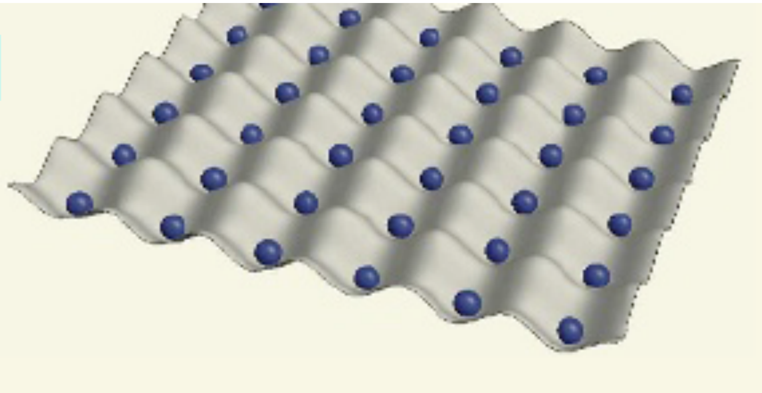
3) Fictitious transverse B field:

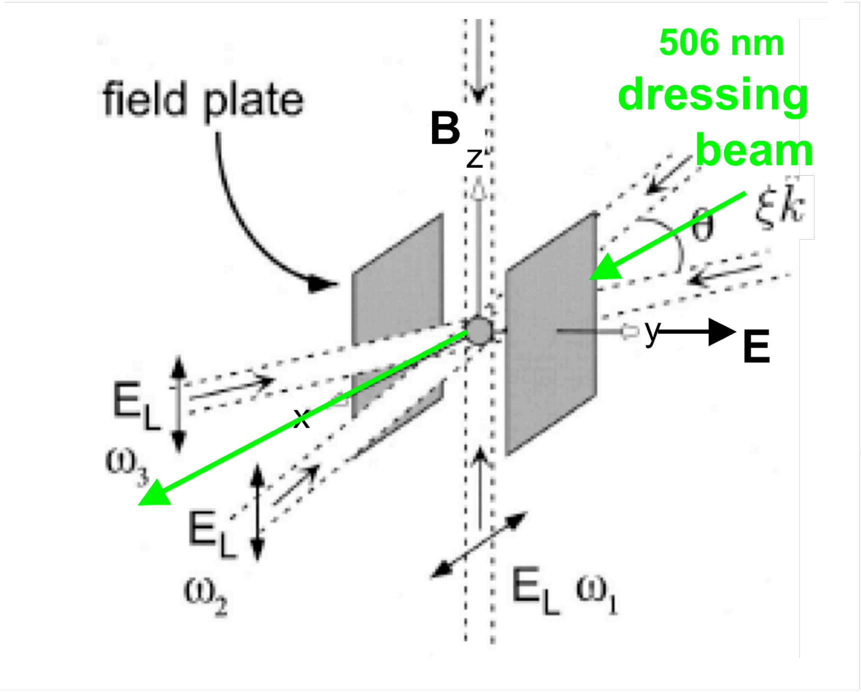
far-detuned allowed transitions are the largest source $B_{ls}\sim$ 30 mG for Fr

B ≥ 50 mG ➔ only small changes of direction of the quantization axis

Measurement on a small sample of cold Fr atoms

e.g. $\approx 10^4$





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

a design proposed to improve precision on the the e-EDM limit
three-D optical lattice

C.Chin, V.Leiber, V.Vuletic, A.Kerman, S.Chu,
PR A **63** 033401 (2001)

Ramsey atomic interferometry

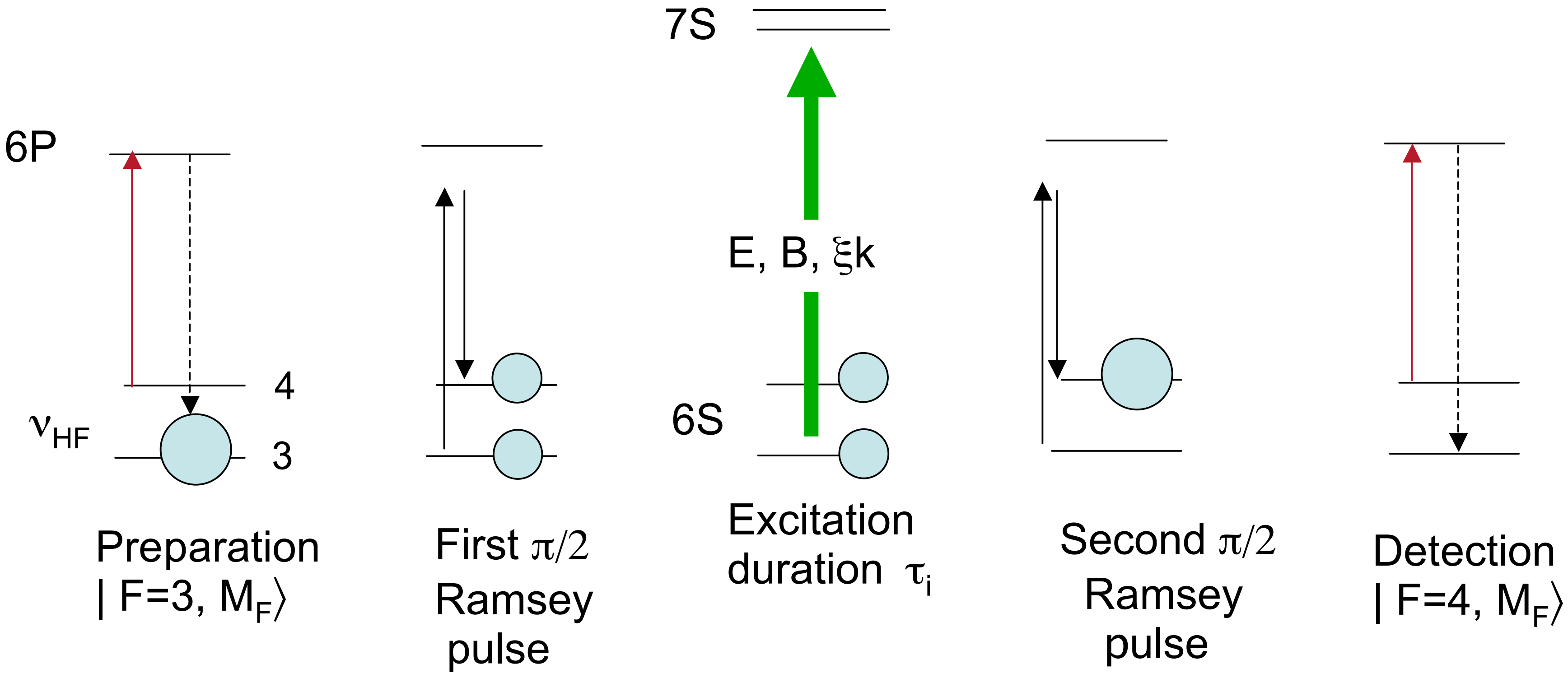
✔ Preparation of a coherent state $(|F,m\rangle + |F',m'\rangle)/\sqrt{2}$ with $F \neq F'\ m = m',\ \ \delta_F < \Delta W$
or $F = F',\ m \neq m'$

✔ Evolution during the interaction time τ_i in presence of 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
4. In a given E, B, ξk configuration measure ν_{HF} 9,2 GHz
5. Repeat in different configurations
6. Extract $\delta\nu_{PV}$ odd in E, B, ξk 5 μHz in Cs, 100 μHz in Fr .



UNCERTAINTIES

Projection noise and Signal to noise

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

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

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

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

$\boxed{N_{at} = 10^4}$ $\boxed{\delta\nu(\mathrm{mHz}) = 2.2\ \tau^{-1/2}}$ for Fr

$\boxed{4\times10^6}$ $\boxed{0.1\ \tau^{-1/2}}$ for Cs

S/N = $\Delta\nu^{pv}_{hf}/\delta\nu = \Omega^{pv}\sqrt{\tau/2\Gamma_{n'S}\sqrt{N_{at}}}$ **≈ 3 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

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: $\pm\ \delta_F$

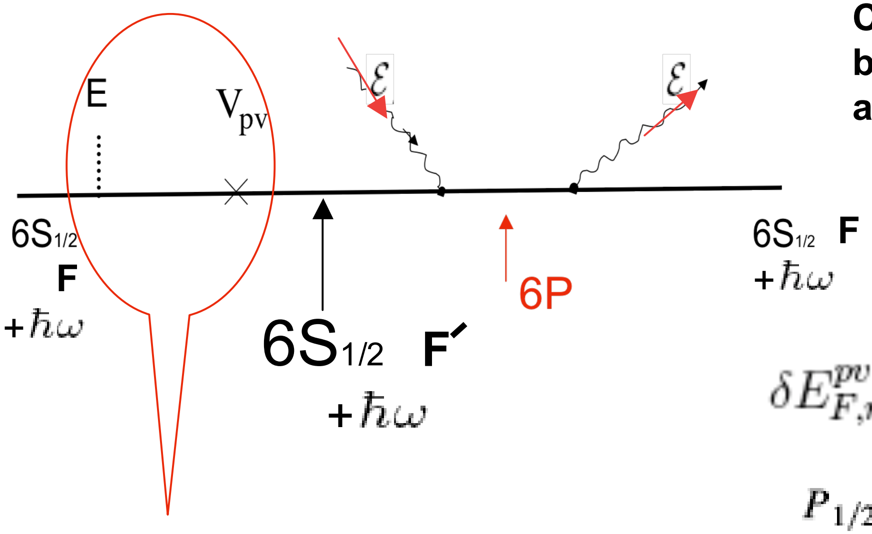
➔ Ratio $\Delta\nu^{pv}_{hf}/\Delta\nu^{ls}_{hf}$ Independent of the beam intensity and position

Possible systematic effect ?

i) A small interaction region is favorable to a good control of the fields

ii) The linear Stark shift associated with the amplitude M_1 : efficiently reduced with multipassages of the beam (or use of a FP cavity) and rotation of the mirrors

The anapole frequency shift

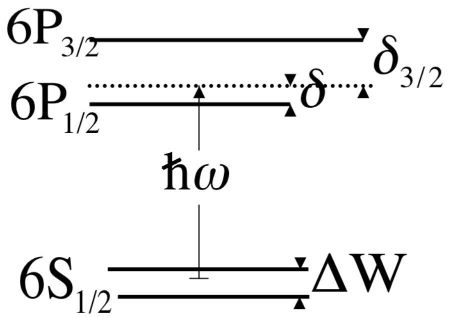


$$V_{ana} = d_I \mathbf{E} \cdot \mathbf{s} \wedge \vec{I}$$

Cs $d_I \simeq 2.36(40) \times 10^{-13}\ |e|a_0$

$$F \neq F'$$

Circularly polarized dressing beam near resonant for the allowed 6S-6P transition



$$\delta E^{pv}_{F,m_F} = \frac{(F-F')}{\Delta W}\langle\alpha|V_{ana}|\alpha'\rangle\langle\alpha'|V_{rad} R V_{rad}|\alpha\rangle + \text{H.c.}$$

$P_{1/2}$ Contribution $R = \sum_m |P_{1/2}, m\rangle\langle P_{1/2}, m| / \hbar\delta$

$$V_{rad} = \Omega_1\, \vec{\sigma} \,.\, \hat{e}(\xi)$$

$$\hbar\Omega_1^2 \vec{\sigma} \cdot \xi \mathbf{k}\ / \hbar\delta$$

$$\delta E^{pv}_{F,m} = 2(F-I)\boxed{(\xi\hat{k} \wedge \hat{E} \cdot \hat{B})}\frac{d_I E \hbar\Omega_1^2}{\Delta W \delta}\langle F, m_F|I_z|F, m_F\rangle$$

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

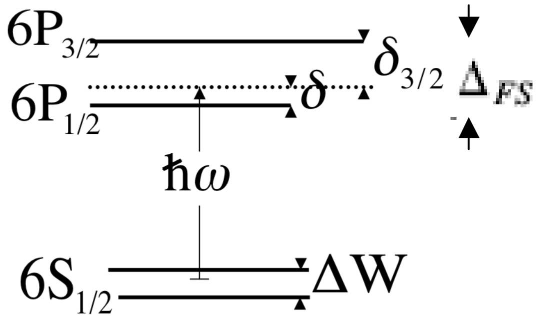
In 10 - 100 μHz range

B is supposed to define the quantization axis **B >** B_{ls}

M.A. Bouchiat PRL, **98,** 043003 (2007)

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

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

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

In Cs

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

$\delta/2\pi = 6.65$ THz

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

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

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**

both P-odd but T-even

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

leading to freq. shifts

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

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

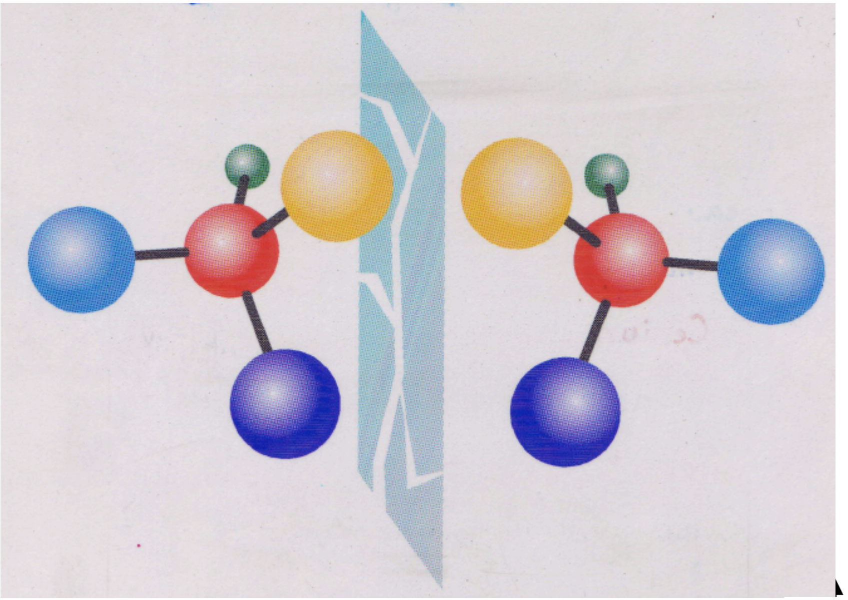
$\mathcal{E} \approx$ 2.2 kV/cm ➔ $T_{\frac{1}{2}} \approx$ 1 s

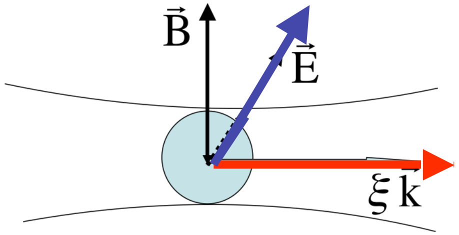
Anapole EDM E ≈ 100 kV/cm, $\delta/2\pi \approx$ 6.6 THz *from the* **resonance line**

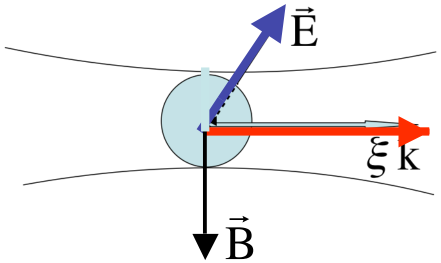
- There are concrete examples where several powerful techniques developed recently in cold atom physics appear as valuable tools for precise APV measurements

Cs atoms do behave similarly as enantiomer molecules

In two mirror-image field-configuration they give shifts of opposite signs.







Thus our goal to transfer APV asymmetry measurements from transition probability to frequency shift domain looks within reach

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

The optimization process : summary

For both the Q_W and the anapole shift an optimization is required.

✔ The dressing field should be large but avoid photoionization
& optical lattice deformation

✔ The Interaction time should match the time between two cycles (duty cycle close to 1)

✔ Once $\mathcal{E}$ and τ_i chosen, then the stability condition implies

— **for the Q_W shift** one relation between ***E*** and a lower limit to $\delta < \Delta W$
involving the magnitude of the dressing field

— **for the anapole shift** a higher limit to $\delta \approx \Delta_{FS}$
depending on the dressing field
E *should be taken as large as possible*

Collaborations having worked or working on francium (Z=87)

Isolde collaboration at Cern (1978-…1990)
Group at Stony Brook:
E. Gomez, L. A. Orozco, G. D. Sprouse, Rep. Prog. Phys. **69**, 79 (2006)
S. Aubin *et al.*, Rev. Sci. Instrum. **74**, 4342 (2003)

LBL Group (C. Wieman, H. Gould et al.)
Legnaro (Italy)
New collaboration at TRIUMF (Canada) embarking in an APV program :

anapole & weak charge

based on L-R anisotropies of the transition rates

Most commonly studied isotopes

	^{210}Fr	^{212}Fr	^{221}Fr	^{223}Fr
Life time (mn)	3.2	19.6	4.9	21.8
Nuclear spin	6	5	5/2	3/2
Hfs splitting (GHz)	46.8	49.8	18.6	15.3
	neutron-odd isotopes		neutron-even isotopes	