ATOMIC PARITY VIOLATION: PRINCIPLES, RECENT RESULTS, PRESENT MOTIVATIONS

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We review the progress made in the determination of the weak charge, Q_W, of the cesium nucleus which raises the status of Atomic Parity Violation measurements to that of a precision electroweak test. Not only is it necessary to have a precision measurement of the electroweak asymmetry in the highly forbidden 6S-7S transition, but one also needs a precise calibration procedure. The 1999 precision measurement by the Boulder group implied a 2.5 σ deviation of Q_W from the theoretical prediction. This triggered many particle physicist suggestions as well as examination by atomic theoretical physicists of several sources of corrections. After about three years the disagreement was removed without appealing to "New Physics". Concurrently, an original experimental approach was developed in our group for more than a decade. It is based on detection by stimulated emission with amplification of the left-right asymmetry. We present our decisive, recent progress together with our latest results. We emphasize the important impact for electroweak theory, of future measurements in cesium possibly pushed to the 0.1% level. Other possible approaches are currently explored in several atoms.

Keywords: Electroweak interference; nuclear weak charge; atomic parity violation; stimulated-emission detection.

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1. Introduction

In this short review paper we intend to survey the theoretical and experimental progress made in Atomic Parity Violation since the emergence of the field in 1974. First (§ 2), we indicate the connection between Atomic Parity Violation (APV) and Electroweak (EW) Theory. Everything centres around one electroweak parameter, the weak charge of an atomic nucleus, Q_W, associated with the exchange of the Z_0 boson between the atomic electron and nucleus. We provide a short background to APV experiments. How can Z_0 bosons affect atomic radiative transitions? How is Q_W extracted from experiment? Besides the measurement of a left-right asymmetry itself, A_{LR}, the theoretical interpretation of the result requires state of the art atomic physics calculations. Then (§ 3) we present past experiments in atomic cesium, the paradigmatic atom for a quantitative test of the EW theory, and discuss their implications. As will be seen in § 4, the apparent deviation between the most precise result by the Boulder group[1,2] and the Standard Model (SM) prediction triggered important theoretical efforts. It also gave additional motivations for our current Cs experiment in Paris, presented next. We show that this experiment now provides valuable PV data by a method totally different from Boulder. We indicate other possible experimental approaches, in different atoms, under current investigation. Finally (§ 5), we dicuss the relevance today of APV experiments.

2. Electroweak parity violation in atoms

For a naive estimate of A_{LR} let us consider two radiative electron-hadron processes (Fig. 1, Left and center), the first one of amplitude A_{em} governed exclusively by electromagnetic interactions, and the second one of amplitude A_W associated with a Z_0 boson exchange. The weak amplitude A_W contains a part which is *odd* under space reflexion, which will give rise to a left-right asymmetry A_{LR} by interference with the dominant electromagnetic amplitude. For two mirror-image experiments we obtain two different transition probabilities: $P_{L/R} = |A_{em} \pm A_W^{odd}|^2$ and we find:

$$A_{LR} = \frac{P_L - P_R}{P_L + P_R} \simeq 2\, Re\left(A_W^{odd}/A_{em}\right) \ . \tag{1}$$

If q denotes the four-momentum transfer between the lepton and the hadron, A_{em} is proportional to e^2/q^2 while $A_W \propto g^2/\left(q^2 + M_{Z_0}^2 c^2\right)$ with $g^2 \approx e^2$, hence $A_{LR} \simeq q^2/M_{Z_0}^2 c^2$. In atoms we expect q to be given by the inverse of the Bohr radius, $\sim m_e \alpha c$. We thus arrive at an exceedingly small value of the asymmetry :

$$A_{LR} \simeq \alpha^2 \frac{m_e^2}{M_{Z_0}^2} \approx 10^{-15} \ .$$

Such a result would appear to make the observation of the left-right asymmetry in atoms completely hopeless. Fortunately there are important enhancement mechanisms which make this naive estimate far too pessimistic. In fact, in actual experiments, A_{LR} can be as large as a few times 10^{-6}.

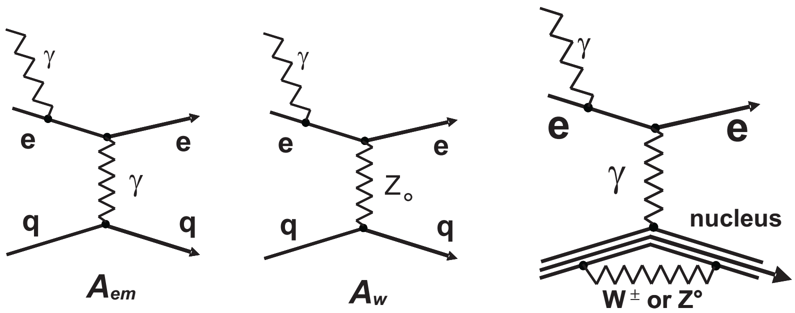

Fig. 1. Left and center: Schematic representation of the two amplitudes, electromagnetic A_{em} and weak A_W associated with a photon or Z_0 exchange between electron e and quark q, which can contribute to the same radiative process and give rise to an electroweak interference. Right: Schematic representation of the nuclear-spin-dependent PV interaction associated with the nuclear anapole moment.

The first source of enhancement finds its origin in the so-called Z^3 law. This law predicted by C. Bouchiat and one of the authors (M.-A. B.) in 1974[3,4] states that the electroweak effects in atoms should grow a little faster than the cube of the atomic number Z. Indeed, for valence electrons belonging to penetrating orbitals, like $s_{1/2}$ or $p_{1/2}$, the orbital is deformed in the vicinity of the atomic nucleus, right where the short range interaction takes place. It looks like the orbital associated with a Coulomb potential of charge Z, whose radius is given by a_0/Z. Hence, in heavy atoms the factor $|q^2|$ is enhanced by the factor Z^2. Moreover, the various nucleons in the atomic nucleus add their contributions coherently. Since, in heavy atoms, the number of nucleons grows roughly as Z, the overall enhancement effect is proportional to Z^3.

For a more quantitative analysis it is necessary to introduce the parity violating electron-nucleus potential which, in the non-relativistic limit, can be written as:

$$V_{pv}(r_e) = \frac{Q_W\, G_F}{4\sqrt{2}} \left(\delta^3(\vec{r_e})\, \vec{\sigma}_e . \vec{v}_e/c + \ h.c. \right) \ . \tag{2}$$

Here we have kept the dominant contribution in which the Z_0 couples to the electron as an axial vector and to the nucleons as a vector. Consequently, the strength of this interaction is naturally expressed in terms of a nuclear charge, Q_W. For the electroweak interaction this charge plays the same role as the nuclear electric charge for the Coulomb interaction. Hence its name, the "weak nuclear charge". Like the electric nuclear charge, Z, the weak charge Q_W is the sum of the weak charges of all the constituents of the atomic nucleus, the u and d quarks :

$$Q_W = (2Z + N)Q_W(u) + (Z + 2N)Q_W(d) \ . \tag{3}$$

In the Standard Model, with the electroweak parameter $\sin^2\theta_W \simeq 0.23$, it so happens that Q_W lies close to the neutron number[a] :

$$Q_W(SM) = -N - Z \left(4 \sin^2\theta_W - 1\right) \simeq -N \tag{4}$$

The second source of enhancement comes from the possibility of exciting highly forbidden transitions like the $6S_{1/2} \rightarrow 7S_{1/2}$ transition in cesium. In a transition such as $6S_{1/2} \rightarrow 7S_{1/2}$ the electromagnetic selection rules strictly forbid the existence of an electric dipole transition. The weak interaction associated with Z_0 exchange breaks this rule and gives rise to a parity violating electric dipole amplitude[b], E_1^{pv}. This E_1 amplitude is of course very small, $\simeq 10^{-11}$ atomic units (ea_0, a_0 Bohr radius). On the other hand, symmetry allows the existence of a magnetic dipole amplitude, M_1. However, because the two states connected by the transition

[a] This formula is valid only to lowest order in the electroweak interaction.
[b] Note that Z_0 exchange gives rise to a transition electric dipole, not to a static electric dipole. The reason is that this PV weak interaction preserves time reversal invariance, while a static dipole would be a manifestation of simultaneous P and T violation. Another consequence of time reversal invariance is that E_1^{pv} is pure imaginary in a phase convention where M_1 is real.[3]

have different radial quantum numbers, the M_1 transition is suppressed: its amplitude is only $4 \times 10^{-5}\ \mu_B/c$, so that we can anticipate a relatively large asymmetry: $Im\ E_1^{pv}/M_1 \simeq 0.5 \times 10^{-4}$. Even today, cesium appears to be a good compromise between a high atomic number necessary to have sizable effects and the simple atomic structure required to make precise atomic calculations.

Once the Z^3 enhancement became apparent, the main question was how best to take advantage of it. There were in fact two different lines of attack. The first takes advantage of highly forbidden M_1 transitions such as $6S_{1/2} \rightarrow 7S_{1/2}$ in cesium. Its merits are the relatively large asymmetry and the simple atomic structure characteristic of an alkali atom which has a single valence electron outside a tight atomic core. This type of transition, however, represented completely new territory and the suppression factor looked absolutely huge, $\sim 10^{14}$, so that one could anticipate difficulties with the signal-to-noise ratio. Nevertheless, this was the approach chosen by our group in Paris and later on by the Boulder group[5]. The forbidden M_1 $6P_{1/2} - 7P_{1/2}$ transition in Tl was selected by the Berkeley group[6]. The second line of attack consists in working with allowed M_1 transitions in atoms of even higher Z such as Tl, Pb and Bi, with Z respectively equal to 81, 82, and 83. The suppression factor is only 10^5 and *a priori* this should avoid the signal-to-noise difficulties. This approach was adopted at Oxford[7], Seattle[8], Novosibirsk[9] and Moscow[10]. Precise measurements in these elements have been achieved, but presently the difficulty lies in the more complicated atomic structure. The accuracy in Q_W is today limited by the precision in atomic calculations. For this reason this presentation is limited to the case of cesium where the most precise determination has been so far achieved. Hereafter, we shall concentrate on the $6S_{1/2} \rightarrow 7S_{1/2}$ transition in cesium, for which $E_1^{pv} \simeq 10^{-11} i\ ea_0$ and $|M_1| \simeq 2 \times 10^4\ |E_1^{pv}|$.

3. APV in the highly forbidden cesium transition: Past results

3.1. *General principle of the Cs experiments*

In order to observe the atomic transition well above the background coming from loosely bound cesium dimers, we apply a static electric field **E**. This field induces a transition electric dipole $\mathbf{d}^{ind}$ via parity-conserving mixing of atomic P states with S states. In this induced dipole

$$\mathbf{d}^{ind} = \alpha \mathbf{E} + i\ \beta\ \vec{\sigma} \times \mathbf{E}\ , \tag{5}$$

there are actually two contributions, one due to the scalar transition polarizability α, and the other to the vector polarizability β. Here $\vec{\sigma}$ stands for the electron spin operator. The coupling of $\mathbf{d}^{ind}$ to the electric radiation field $\hat{\epsilon}_{ex}$ provided by a resonant laser wave, gives rise to an induced electric dipole amplitude, $E_1^{ind} = \mathbf{d}^{ind} \cdot \hat{\epsilon}_{ex}$. An excellent control of E_1^{ind} can be achieved by adjusting the strength of **E**, its direction with respect to both the direction of the light beam and the beam polarization $\hat{\epsilon}_{ex}$. Reversing the direction of **E** can even give a specific signature to all effects linear in E_1^{ind}. For all these reasons $E_1^{ind} E_1^{pv}$ has become the kind of interference effect detected in all cesium APV experiments so far. The transition rate $|E_1^{ind}|^2$ grows like the square of the electric field, while the asymmetry E_1^{pv}/E_1^{ind} is inversely proportional to the field, but still can reach values above 10^{-6}.

Experiments only measure amplitude ratios like $Im\ E_1^{pv}/\beta E$ and since β is known from atomic theory only to within 1% accuracy, there was a crucial need for an accurately known amplitude usable for *absolute calibration.* Fortunately, as shown in 1988 by our ENS-Paris group[11,12], a very precisely known transition amplitude does exist. In zero electric field the $M_1\ 6S_{1/2} \rightarrow 7S_{1/2}$ Cs transition amplitude contains a certain contribution $M_1^{hf} \simeq 0.19 \times M_1$, induced by the off-diagonal hyperfine interaction. Experimentally this contribution is easily identified because it contributes only to the $|\Delta F| = \pm 1$ hyperfine lines and with opposite signs. The key-point is that, up to corrections less than 0.25% coming from many-body effects[11,13,14], M_1^{hf} can be expressed in terms of the geometrical mean of the diagonal matrix elements[11], *i.e.* the hyperfine splittings ΔW of the two S states, themselves measured in cesium with high precision: $M_1^{hf} = C\sqrt{\Delta W_{6S} \cdot \Delta W_{7S}}$. Finally, as advocated in ref.[12], a precise measurement of M_1^{hf}/β then provides an *absolute* determination of β thereby making possible an absolute determination of E_1^{pv} with a theoretical uncertainty less than 2.5×10^{-3}.

As a last step, Atomic Physics calculations are essential to extract Q_W from the experiment. The quantity E_1^{pv} can be considered as an infinite sum over the intermediate P states admixed with the S states by the parity-violating interaction :

$$E_1^{pv} = \sum_n \frac{\langle 7S_{1/2}|\, d_z \,|nP_{1/2}\rangle \langle nP_{1/2}|\, V_{pv} \,|6S_{1/2}\rangle}{E\left(6S_{1/2}\right) - E\left(nP_{1/2}\right)} + \text{ crossed terms .}$$

The atomic orbitals and the valence-state energies are perturbed by many-body effects. Initially, two different approaches have been employed, one semi-empirical[15], and the second starting from first-principles[16,17], following techniques inspired from field theory to perform relativistic many-body computations (see §4.1 for more details). Results agree within the stated precision.

3.2. *Completed Cs experiments: the very first in Paris, and a high precision one in Boulder*

The experiment completed in Paris[18], in 1982 and 1983, was the first carried out in cesium. The detected signal was the *circularly polarized* fluorescence on the $7S_{1/2} - 6P_{1/2}$ transition following circularly polarized 6S-7S excitation in a transverse $\mathbf{E}$ field. With 12 % experimental accuracy and a theoretical uncertainty at that time less than 8 %, it has led to a quantitative test of the standard electroweak theory in the electron-hadron sector, which is of a new kind[3]. Because of the low momentum transfer involved ($\simeq$ 1 MeV/c) it extends considerably the range of $|q^2|$ where the theory finds experimental support. Moreover, information deduced from Q_W complements that obtained from high energy experiments because, as mentioned above (Eq. 3), in atoms all the nucleons and all the quarks act coherently[19].

In particular, it provides a test for additional neutral vector bosons. This point will be discussed for the present context in the last section.

APV can also be a source of valuable information relevant for nuclear physics, via the nuclear-spin-dependent PV interaction. The relevant experimental parameter involved here, is the difference between the two asymmetries measured on two different hyperfine lines belonging to the same transition[c]. If non-zero, the quantity:

$$r_{hf} = \frac{A_{LR}(6S \rightarrow 7S, \Delta F = -1)}{A_{LR}(6S \rightarrow 7S, \Delta F = +1)} - 1 \ , \tag{6}$$

is a manifestation of the nuclear-spin-dependent interaction. An effect of about 4% is expected as a result of the parity violating interactions taking place inside the nucleus between the quarks. The valence electron is contaminated by photon exchange (see the corresponding diagram represented on Fig. 1, right). The theoretical concept relevant for describing this effect is the nuclear anapole moment, introduced a long time ago by Zel'dovich[20]. For a simple interpretation in terms of chiral magnetization of the nucleus the reader is referred to[21]. Explicit calculations have been performed for cesium by the Novosibirsk[22] and Paris[23] groups. It is interesting to note that the effect of the electron-nucleus Z_0 exchange associated with an axial-vector coupling to the nucleons, also involving the nuclear spin, is formally identical but about five times smaller.

In 1997 precision measurements of $Im \ E_1^{pv}/\beta$ on the two hyperfine lines $\Delta F = \pm 1$ were made by the Boulder group[2]. This experiment operates on a spin polarized atomic beam that crosses an optical power build-up cavity resonant for the 6S-7S transition. DC electric and magnetic fields, $\mathbf{E}$ and $\mathbf{B}$ are applied perpendicularly to the angular momentum, $\xi\mathbf{k}$, of the resonant light beam. The pseudo-scalar quantity which manifests PVis the mixed product: $\mathbf{E} \times \mathbf{B} \cdot \xi\mathbf{k}$. It is expected to appear in the transition rate of single Zeeman components of the transition. One monitors a change in the ground state population induced during passage through the interaction region which is correlated with the parameter reversals. Combining the results quoted for the two hyperfine lines $\Delta F = \pm 1$, one can extract the nuclear-spin-independent contribution:

$$Im \ E_1^{pv}/\beta = (-1.5963 \pm 0.0056) \ \mathrm{mV/cm},$$

discussed later on, as well as the r_{hf} parameter (Eq. 6):

$$r_{hf} = (4.8 \pm 0.7) \times 10^{-2} \ .$$

This last result provides a clear manifestation of the nuclear anapole moment. However, it appears inconsistent (roughly by a factor of 2) with other data relating to PV nuclear forces[23,24]. So an independent measurement looks necessary.

[c]The cesium natural isotope having the nuclear spin 7/2, the $6S_{1/2}$ and $7S_{1/2}$ states possess two hyperfine substates with total angular momentum F =3 and 4.

Using their very precise measurement of M_1^{hf}/β performed more recently[1] (quoted accuracy of 0.12 %) and the atomic theory at that time, the result for the weak charge finally reported by the Boulder group is :

$$Q_W^{exp} = -72.06 \pm 0.28_{exp} \pm 0.34_{th} \ .$$

Note that the theoretical uncertainty of 0.4% quoted here is 2.5 times smaller than the 1% uncertainty estimated by the theoreticians, but it was assigned by the group based on the ability of the theoretical models to reproduce atomic test parameters[1]. When the errors of different origins are added in quadrature, the fractional accuracy is 0.6%. This result has to be compared to the SM prediction[25], recently updated[26]:

$$Q_W^{th} = -73.19 \pm 0.13.$$

A deviation between experiment and theory of 1.13 = 2.6 σ was concluded. The existence of an extra neutral gauge boson[27], whose mass lies in the range hundreds of GeV, was invoked as a possible interpretation in terms of "new physics" beyond the Standard Model, that did not contradict high energy physics results.

4. New activity in the field

4.1. *Atomic theory*

The 0.4% theoretical uncertainty assigned on Q_W^{exp} by the Bouder group raised questions about small corrections to the prediction neglected so far. This prompted several theoretical groups to reconsider the problem.

A. Derevianko[28] was the first to evaluate the Breit correction (the magnetic interaction between all electrons) and to announce a non-negligible correction to $Q_W^{exp} \simeq -0.6\%$, rapidly confirmed by other groups[29,30]. The effect of a difference between the neutron and proton distributions, already examined[17], was revisited and confirmed to be small for cesium, -0.2% with an uncertainty $\lesssim 0.1\%$[30−33].

Theorists of relativistic many-body calculations have refined their calculations and still agree on the result within a 1% level of precision[29,34,30], with a precision of 0.5%[30] being claimed. In addition, the last calculations now include the contribution of self-energy and vertex QED radiative corrections[35,36] found to be non-negligible (-0.85%).

Once reinterpreted at the light of the latest theoretical results, Q_W^{exp} becomes:

$$Q_W^{exp} = -72.71 \pm 0.29_{exp} \pm 0.39_{th} \ .$$

The current deviation $Q_W^{exp} - Q_W^{th}$ is thus less than one σ[24]. In view of this new result, the lower limits on the mass of a possible Z' boson have been reanalyzed[37] and found comparable to those deduced from the four LEP experiments.

In spite of this apparently perfect agreement with the SM, we would like to underline two reasons (one theoretical and the other experimental) why it may be somewhat too early to consider such an agreement as definitely well established.

(i) A slight risk of double counting in the radiative-correction evaluation: not only the atomic factor but also Q_W^{th} include QED radiative corrections. A global calculation incorporating all corrections to the parity violating electron-nucleus interaction would seem to be more rigorous.

(ii) Necessity of independent measurements.

(a) Cross-check of the empirical ratio β/M_1^{hf} seems important. When the precise Boulder determination of β/M_1^{hf} is used to obtain a value for the vector polarizability β, the result differs from a recent semi-empirical determination of β[38] by $(0.7 \pm 0.4)\%$. Though small, such a difference, considered alone, is sufficient to shift the value of Q_W^{exp} by $1.3\,\sigma$[30].

(b) An independent determination of Q_W^{exp} using a totally different method would be welcome as a cross-check. Our current experiment developed at ENS-Paris should actually fulfill this objective.

4.2. *A novel experimental approach: APV measured in Cs using stimulated-emission detection and asymmetry amplification*

Our new experiment currently performed on the Cs $6S \to 7S$ transition differs radically from both our first 82-83 experiment[18] and the Boulder experiment[2]. While all APV experiments on highly forbidden transitions in a Stark field have used so far the detection of fluorescence signals, this experiment exploits the possibilities of the Λ-type three-level system $6S_{1/2}$–$7S_{1/2}$–$6P_{3/2}$ in interaction with two copropagating lasers. One intense laser with linear polarization $\hat{\epsilon}_{ex}$ excites the forbidden transition in a longitudinal $\mathbf{E}$ field and the second laser probes the angular anisotropy induced in the excited state. The probe laser is amplified and its linear polarization $\hat{\epsilon}_{pr}$ is altered. A precise analysis of the polarization change is performed on the transmitted beam. In order to provide suitable conditions for PV measurements, a large gain for the probe has to be achieved, hence the realization of this experiment with a pulsed excitation laser and a gated probe. The left-right asymmetry is a rotation of the linear polarization of the probe $\hat{\epsilon}_{pr}$, which can be measured at each laser pulse with a dual-channel polarimeter operating in balanced mode (see Fig. 2). The effect is the manifestation of the pseudoscalar $(\hat{\epsilon}_{ex} \cdot \hat{\epsilon}_{pr})(\hat{\epsilon}_{ex} \wedge \hat{\epsilon}_{pr} \cdot \mathbf{E})$ present in the optical gain, i.e. a *chiral* term which is responsible for contributions of opposite signs to the amplified intensity detected in both channels[39].

This *chiral* optical gain can be understood on the basis of simple symmetry considerations. The excitation polarization $\hat{\epsilon}_{ex}$ and the $\mathbf{E}$ field determine two symmetry planes for the experiment. Without parity violation one would expect the excited Cs vapor to have its optical axes contained in those planes. If this were the case, a probe beam linearly polarized with $\hat{\epsilon}_{pr} \parallel \hat{\epsilon}_{ex}$ would pass through the vapor without alteration of its polarization. Actually, due to parity violation acting during the excitation process, the optical axes of the excited vapor are tilted with respect to the symmetry planes and it is this tiny tilt angle $\theta^{pv} = -Im\ E_1^{pv}/\beta E \simeq 10^{-6}$ rad, odd under $\mathbf{E}$-reversal, which has to be determined. As a consequence of this tilt, while

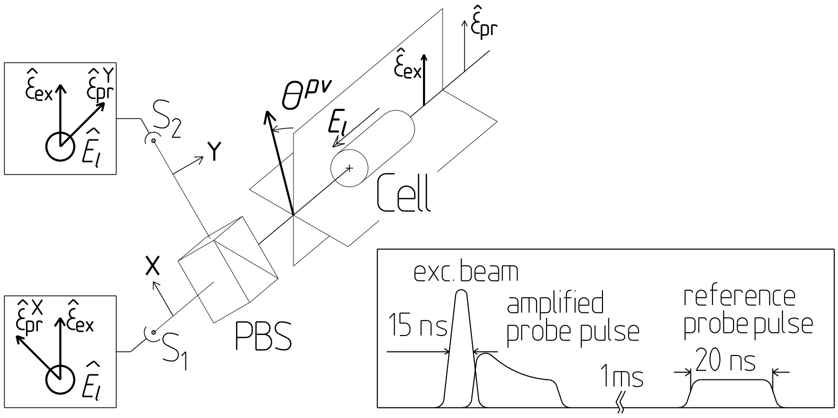

Fig. 2. Schematic of the ENS-Paris pump-probe Cs experiment showing the two orthogonal symmetry planes defined by the electric field **E** and the linear excitation polarization $\hat{\epsilon}_{ex}$. APV gives rise to a tilt θ^{pv} of the optical axes of the excited vapor out of those planes. The incoming probe polarization $\hat{\epsilon}_{pr}$ provides a superposition of the right- and left-handed $(\hat{\epsilon}_{ex}, \hat{\epsilon}_{pr}, \mathbf{E})$ configurations analyzed. The probe amplification difference is directly extracted from the optical signals S_1, S_2, recorded in each channel of the Polarizing Beam Splitter (PBS). Inset: timing of the experiment repeated at $\sim$ 150 Hz. (Fig. adapted from Guéna *et al.*[39]).

the probe beam passes through the vapor its polarization rotates towards the axis of larger gain. This causes an imbalance at the output of the polarimeter, odd in **E**-reversal, which is measured. It is precisely calibrated by measuring the imbalance induced by a small precisely known tilt of $\hat{\epsilon}_{ex}$, in identical conditions.

An attractive feature of this experiment is that *the left-right asymmetry* itself, A_{LR}, is amplified while the probe propagates through the optically thick vapor. Therefore, instead of being a decreasing function of the applied field as in usual fluorescence experiments, A_{LR} is transformed by stimulated-emission detection into an increasing function of $|\mathbf{E}|$[40]. Another conceptual difference with the Boulder experiment is that the detected observable is directly the asymmetry itself as opposed to a modulation of order 6×10^{-6} in the total transition rate, correlated with parameter reversals. Moreover, the present approach avoids the difficulty met there regarding systematics associated with M_1 interference effects and line-shape dependent effects. Another attractive feature is the cylindrical symmetry exhibited by the experiment: the signal is expected to remain invariant under simultaneous rotations of the laser beam polarizations $\hat{\epsilon}_{ex}, \hat{\epsilon}_{pr}$ about the common beam direction. This feature enables us to discriminate against possible systematics arising from stray transverse fields and misalignments[41].

However, the observation of the PV *chiral* optical gain remains an experimental challenge[42]. For instance, detection has to be restricted to the $\sim$ 20 ns time interval during which the pulse excited vapor acts as an amplifier. This is achieved using a fast optical switch on the probe laser beam, with severe requirement with respect

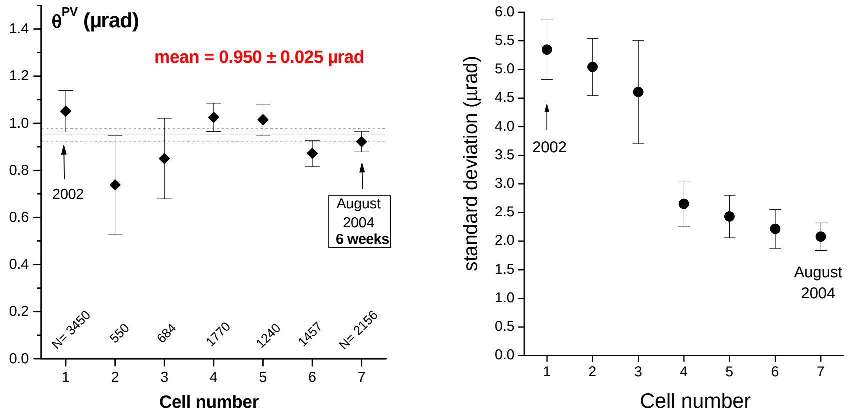

Fig. 3. Results of the ENS experiment. Left: Values of $\theta^{pv} = -Im\ E_1^{pv}/\beta E$ obtained in different Cs cells: mean (diamond) and statistical error (error bar) from the sample of N data acquired in each of the 7 cells. Solid and dashed lines: global mean and statistical error, respectively. Right: Standard deviation of the distribution of the PV data relative to each cell. Adapted from Ref.[43].

to its extinction ratio[43]. Among several other unusual problems to be solved, there was the generation of a pulsed longitudinal uniform **E** field of 2kV/cm inside a 8-cm long Cs vapor cell at the useful atomic density and submitted to intense laser light pulses. One key-element here was provided by the all-sapphire so-called "grooved" cells, finally upgraded with high optical quality metal coated windows. An original trick to enhance the signal has been the use of a polarization-tilt magnifier.

Fig. 3, Left summarizes the experimental determinations of $\theta^{pv} = -Im\ E_1^{pv}/\beta E$ obtained in seven different cesium vapor cells, which are well compatible (χ^2=7.7 for 6 degrees of freedom). The experiment provides for real-time tests of the systematic effects and consistency tests in the data reinforcing confidence in the results[43]. Using our 1% accurate *in-situ* determination[43] of the Stark induced amplitude βE in terms of the precisely known (see § 3.1) M_1 amplitude, our present result for the $6S_{F=3} \to 7S_{F=4}$ hyperfine component is

$$Im\ E_1^{pv} = (-0.808 \pm 0.021) \times 10^{-11}\ ea_0$$

or, relying on the determination of β in Ref.[1]:

$$Im\ E_1^{pv}/\beta = (-1.538 \pm 0.040)\ \mathrm{mV/cm}\ .$$

It is affected with negligible systematic uncertainty and reaches a 2.6% statistical accuracy. It agrees well with the Boulder result $Im\ E_1^{pv}/\beta = (-1.558 \pm 0.008)$ mV/cm for the same component. The *absolute* precision of $2 \times 10^{-13} ea_0$ for $Im\ E_1^{pv}$ is already 10 times better than that achieved in other heavier atoms (Tl, Pb and Bi)[3].

Fig. 3, Right exhibits the improvement on Signal-to-Noise from the first[39] to the last cell : it implies that the averaging time needed to reach a given statistical accuracy is reduced by a factor of ~ 12. This gain in sensitivity has been obtained by our exploiting the process of asymmetry amplification by stimulated emission. The level of sensitivity is now adequate for a one-to-two percent Q_W-precision objective. There is still room for improvement by boosting the amplification phenomenon, for instance in a new *transverse* field geometry as we have proposed recently[44]. In this proposal, a 0.1% statistical precision looks achievable.

The work reported in this section has demonstrated an original method for parity violation measurements in a highly forbidden atomic transition offering perspectives for high precision and reliability.

4.3. *Experiments in progress in other atoms and new proposals*

4.3.1. *Work in progress on a chain of rare earth isotopes*

It has not been possible, yet, to test experimentally an important prediction of the SM concerning the variation of Q_W along a string of isotopes. It has been suggested[45] that in rare earth spectra one can find atomic states of opposite parity which are nearly degenerate, for instance in Dy (Z=66) and Yb (Z=70) which both offer a chain of seven stable isotopes. One expects this near-degeneracy to enhance the PV effect, thus making possible precise measurements. In first approximation, ratios of E_1^{pv} amplitudes should provide ratios of the weak charges, without invoking atomic physics calculations[46], made complex by configuration mixings.

The search in Yb, conducted in Berkeley[47], presents analogies with that performed in Cs. The spectrum of this atom is much simpler than that of other rare earth atoms, so that the theoretical predictions should be more reliable. In the chosen transition, E_1^{pv} is predicted to be 100 times larger than in Cs. Important exploratory work has already been carried out and the M_1 amplitude of this highly forbidden transition has already been measured[48].

4.3.2. *Prospects with cooled and trapped atoms*

Cooling and trapping techniques open the way to measurements with radioactive cesium isotopes or even francium atoms. With Z=87, Fr is expected to lead to PV effects 18 times larger than Cs (Z^3 law and relativistic effects[3], § 3.1). In addition, Fr has many isotopes.

Fr atoms, either obtained from a radioactive source or produced on-line by an accelerated ion beam colliding a target, are produced at a limited rate with a superthermal velocity distribution. The first prerequisite is to avoid their spreading out in space and loss inside the wall. Successive attempts to load Fr atoms in a neutral atom trap have already made possible the observation of several Fr allowed transitions, leading to precise spectroscopic measurements[49,50]. In our opinion, the observation of the forbidden $6S \rightarrow 7S$ line with a sample of cold Cs atoms would represent an important preliminary step to assess the feasibility of a PV measurement in the Fr $7S \rightarrow 8S$ forbidden transition (for a definite proposal, see[51]).

4.3.3. *Static manifestations of the electroweak interaction*

When an atom is placed in a chiral environment, Sandars' theorem[52] no longer holds and Parity Violation can manifest itself by an energy shift of its atomic levels in spite of T-invariance. Although shifts of this kind still require considerable experimental efforts to be detected, their existence presents undoubted conceptual interest.

For chiral molecules one expects a small energy shift between the two mirror-image enantiomers. It has been searched for by comparing vibrational frequencies of the right and left-handed species of CHFClBr molecules[53]. Experiments in more favorable conditions are in progress.

When Cs atoms are trapped in a solid matrix of ^{4}He of hexagonal symmetry, two applied $\mathbf{E}$ and $\mathbf{B}$ static fields and the crystal axis $\hat{n}$ create a chiral environment around each atom. In these conditions, a linear Stark shift proportional to the Cs nuclear anapole moment and to the (T-even) P-odd pseudoscalar $(\hat{n}\cdot\mathbf{B})(\hat{n}\cdot\mathbf{B}\wedge\mathbf{E})/B^2$ has been predicted[54].

Both effects could provide *a static manifestation of the electroweak interaction*, which is still missing.

5. Relevance of Atomic Parity Violation today

The main goal of Atomic Parity Violation[3] is to provide a determination of the weak nuclear charge Q_W, from the measurement of E_1^{pv} *via* an atomic physics calculation which now aims at 0.1% precision in cesium[55]. In view of present and forthcoming results from high energy experiments, an important issue concerns the relevance of further improving difficult experiments such as APV measurements. We would like to present arguments in favor of small scale APV experiments.

(i) First we wish to reiterate that APV experiments explore the electroweak (EW) electron-hadron interaction within a range of low momentum transfers q_{at} of 1 MeV or there abouts in cesium, as opposed to the huge ones explored in collider experiments: 100 GeV at LEP I and LEP II and 1 TeV at LHC. To obtain relevant information, one has to approach an absolute precision of 10^{-8} in the measurement of a radiative atomic transition left-right asymmetry.

(ii) For $q_{at} \sim 1$ MeV, the quarks of the atomic nucleus act *coherently*, while at high energies the nucleons are broken into their fundamental constituants: the quarks act then *incoherently*. This is what happens in deep inelastic electron-nucleon scattering, such as the SLAC experiment[56] involving a GeV polarized electron beam colliding against a fixed deuterium target. As a consequence, different combinations of electron-quark PV coupling constants are involved in the LR asymmetries of the two experiments: $\frac{2}{3}C_u^{(1)} - \frac{1}{3}C_d^{(1)}$ at high energies instead of $(2Z+N)C_u^{(1)} + (Z+2N)C_d^{(1)}$ for Q_W. It is easily seen that, in a model-independent analysis, the two experiments delimit nearly orthogonal allowed bands in the $[C_u^{(1)}, C_d^{(1)}]$ plane[3].

(iii) The fact that $q_{at} \sim$1 MeV allows one to investigate the possible existence of a

light extra neutral gauge boson, for instance with a mass in the range of a few MeV. Such a drastic modification of EW interactions appears as an alternative explanation for the remarkably intense and narrow gamma ray line emitted from the bulge of our galaxy, close to the energy of 511 keV which coincides with the electron mass[57,58]. According to this somewhat exotic model, the observed spectrum would result from the annihilation of two *light dark matter particles* (mass $\geq$ 1-2 MeV) into a pair (e^+, e^-) via the exchange of a light gauge boson U, with a mass of about 10 MeV[59]. In order to reproduce the size of the observed effect, one has to exclude at a large confidence level an *axial* coupling of the electrons to the new U boson, while such a coupling is the only possible one for *dark particles* which carry no charge. This is where APV comes into play.
The most plausible conclusion to which the present value[24] of ΔQ_W leads is that the U boson couples to the electron as a vector particle with no axial coupling at the 10^{-6} level, while its vector coupling to leptons and quarks are of the same order of magnitude[60]. Thus, the APV measurements provide an empirical justification for a key-hypothesis, introduced in the astrophysical model accounting for the 511 keV galactic line.

(iv) Deviations ΔQ_W of Q_W^{exp} from the SM prediction, are most often analyzed in the framework of *"new physics"* models which affect EW interactions *at energies higher than* $M_{Z_0}c^2$ through the existence of gauge bosons heavier than the Z_0, such as for instance Kaluza-Klein excitations of the SM gauge bosons[61]. It turns out that ΔQ_W is proportional to the same factor $X = \frac{\pi^2}{3n} R_{\|}^2 M_{Z_0}^2$ as the deviations from the SM in existing collider experiments, provided that $q^2 R_{\|}^2 \ll 1$, where $R_{\|} \leq 1$ TeV^{-1} stands for the compactification radius associated with the additional $d_{\|}$ dimensions of the new physical space for EW gauge fields. A determination of ΔQ_W below the 0.1 % level of precision would give constraints on $R_{\|}$, competitive with those of LEP II[62,63,64]. Furthermore, one can consider models which predict effects undetectable by LEP II results but that would be visible in APV experiments[62,65]. Therefore, a 0.1% accurate determination of Q_W^{exp} could allow one to impose a ~ 5 TeV limit to the compactification mass $R_{\|}^{-1}$ in a direction possibly invisible to high energy experiments.

In view of the present need for further measurements, underlined above, there are strong incentives to pursue APV measurements in Cs by stimulated-emission detection and to push further the technologies opening the path to novel-type experiments, both in cold radioactive atoms and chains of rare earth isotopes. We find it remarkable that results of APV experiments that involve scattering photons, of only a few eV, by a sample of a few cubic centimeters of dilute atomic vapor, can stand comparison with experiments performed in colliders of the highest energy, for providing a lower limit on the mass of a hypothetical additional neutral boson.

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