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Atomic parity violation. Early days, present results, prospects

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Summary. — This is a personal recollection of the time when the search for APV was beginning. In spite of today's remarkable results, summarized here, there are still important goals to be achieved. I indicate a possible way to tackle the remaining experimental challenges, by adapting methods now of frequent use in precision metrology.

PACS `11.30.Er` – Charge conjugation, parity, time reversal, and other discrete symmetries.
PACS `32.90.+a` – Other topics in atomic properties and interactions of atoms with photons.

1. – The early days

As is well known among the community, T. D. Lee and C. N. Yang were the first to express doubts about the conservation of parity in weak processes. They also indicated how significant experimental tests should be performed. Two systems initially symmetric are allowed to evolve under the interaction to be tested. If there exists a left-right (L-R) asymmetry in the final state, there is parity violation (PV). One of the experiments they suggested was performed the following year (1957) by Chien Shiung Wu, who reported a nearly maximum asymmetry in the β-disintegration of polarized ^{60}Co nuclei!

This was a great shock in the domain of concepts affecting the whole physicist community. Nevertheless, by the end of the 60's, atomic physicists did not feel directly concerned. An atomic preference between left and right appeared extremely unlikely. An atom exhibits a high degree of symmetry and is governed by electromagnetic (EM) interactions well-known for making no distinction between left and right. However, in the mid 1970's considerable efforts were being engaged to test parity conservation (PC) in atoms: after all, an atom is not a purely EM system, what can be expected from the other interactions, in particular weak interactions? Could they perturb the electron orbitals when they approach the nucleus? If so, PV might occur! Things went so fast that by the end of the 70's, when experiments reported the *absence* of PV effects in atoms, there was considered to be a weak link in the chain of theoretical reasoning...

But a few years later several groups were able to confirm, in several atoms, the existence of atomic PV. Such results complement the spectacular successes of the Standard Model (SM) unifying EM and weak theories, which culminated with the discoveries of the W's and Z_0 in high-energy experiments. Indeed, atomic experiments, performed at much lower energies, test long distances and provide information of a different nature.

The sudden motivation for testing PV in atoms resulted from the revolutionary ideas which accompanied the emergence of the electroweak theory, accounting for both EM and weak interactions in a single mathematically coherent framework. Before, weak processes were considered as being mediated only by the charged $W^{\pm}$ bosons, which make the atom unstable, so that it was taken for granted that W interactions and their associated PV feature were not relevant to the physics of stable atoms. Later, the crucial point became the theoretical prediction of the existence of a third heavy gauge boson, carrying no electric charge, the Z_0 which mediates a weak force of a novel kind, so-called Neutral Current (NC) interaction. In this case, there would no longer be anything to prevent the electron from feeling its effect inside an atom. However, when the search in atoms started (at ENS in 1973), the discovery of NC at Gargamelle still looked extremely hypothetical and raised many questions: did NC exist with neutrinos or only with charged particles? Bearing in mind the size of the interaction range, only 10^{-8} to 10^{-7} times the atomic radius, would the effect, if ever present in atoms, be much too small to be detected?

In atoms the L-R asymmetries $\mathcal{A}_{LR}$ are extremely tiny, no more than 10^{-6}, just nothing in comparison with the asymmetry measured in Mrs. Wu's experiments! The reason is that the electron-nucleus Z_0-exchange always competes with photon exchange, whose probability amplitude is stronger by many orders of magnitude. Thus their interference leads to such small PV asymmetries, in great contrast with β-decay involving the PV and PC *weak amplitudes* of similar magnitudes. Fortunately, there are large enhancement effects (pointed out in [1]): i) the asymmetry in heavy atoms, of atomic number Z, grows faster than Z^3 and 2) it is possible to work on highly forbidden transitions where A_{EM} is strongly inhibited. The $6S_{1/2}$–$7S_{1/2}$ cesium transition combines both advantages. Even so, the transition rate is so small $10^{-6}\,\mathrm{s}^{-1}$ that problems with the counting rate could be anticipated. To overcome this difficulty, we proposed the Stark interference method [1], which turned out to be successful: the PV signal acquires a new characteristic feature and the E-field magnitude is easily adjusted to optimize the detection conditions.

Claude and I, started to investigate the Cs suggestion, theoretically, in the fall of 1972. In june 1973, I submitted an order to Spectra-Physics for their newly commercialized color-center laser (the first in France!). A presentation of the project was first given at a Trieste Conference by Claude in the presence of Salam, who made encouraging comments. Then, with Lionel Pottier, who had just completed his thesis and his military service, we built the first experiment. Progress was made against all odds. The laser, first, delivered no light at 539 nm, the Cs transition wavelength... This was just the beginning of a long struggle to make it work and construct two other essential devices: the high-purity polarization modulator and the multipass Cs cell with birefringence-free internal mirrors.

We succeeded to validate the Stark interference method in 1976, by applying it to the measurement of the Cs forbidden M_1 amplitude [2]. In July 1976, an animated session took place at the Atomic Physics Conference in Berkeley. I discovered that Gene Commins and his graduate student, Steve Chu, had started an experiment on the Tl $6P_{1/2}$–$7P_{1/2}$ M_1 line, also among our initial proposals [1]. Big efforts to search for an optical rotation signal on allowed M_1 transitions in Bi were also reported. Several tests in hydrogen and muonic atoms were proposed with a few of them already underway. The field was gathering momentum. Moreover, Jean Brossel, Head of the lab, who made an

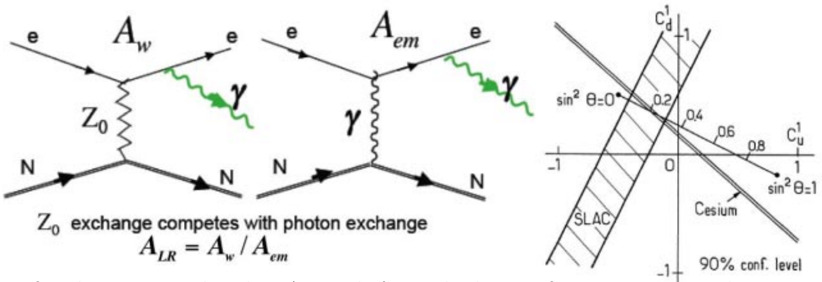

Fig. 1. – Left: the two amplitudes A_w and A_{em} which interfere in atoms and give rise to APV; Right: domains delimited in the C_u^1, C_d^1 plane by APV results in Cs and SLAC results [5].

inquiry to make up his opinion about our project, received very encouraging comments from Steve Weinberg. In his answer, Weinberg insisted on the need for experiments proving that NC interaction does take place at the expected level between electrons and nucleons and showing whether they violate Parity, “since this would immediately rule out the vector model”. However, by the end of that same year, absence of any PV effect in Bi was announced by two groups... though it did not deter the other groups’ efforts.

In September 1979 an important workshop was organized in Cargèse, by W. Williams, who passed away far too early. This was the very first time that our two communities, Atomic Physicists and High Energy Physicists involved in parity violating electron scattering (PVES), met together [3]. Charles Prescott reported the first observation of a PV asymmetry in inelastic polarized-electron scattering on deuterons at high energies, with 10% statistical accuracy and negligible systematics. Another event was the participation of our Russian colleagues not allowed to travel before... The three Bi groups presented positive results, some of them still preliminary. From lively discussions it emerged that the first observation of a manifestation of weak interaction in a purely atomic process had been achieved. But there was still a disturbing factor of 2 of discrepancy between the two groups in Seattle and Oxford and the Novosibirsk group. In Tl, a 2-σ effect was reported, followed by a 3-σ one the following year [4] (see table 1 in [5]). Soon, our efforts gained driving force with the arrival of Jocelyne Guéna, as PhD student but later a mainstay of the group, and Larry Hunter, as a Post-Doc from Pr. Commins’ group.

Our first Cs result came next in 1982 [6], but it arrived with a 6σ statistical accuracy and a very detailed analysis of systematic uncertainties, obtained by recording during data acquisition all the instrumental imperfections which may contribute to detrimental effects [6]. Once this result combined with that of a second measurement obtained in 1983 on a different hyperfine component, and interpreted using atomic calculations, (then 12% accurate), it was becoming possible to make a comparison with the SM model prediction. This was the first quantitative test of this model at low energies. Its complementarity with the SLAC experiment is illustrated in fig. 1.

2. – Present results

In atomic physics, the Z_0 electron-nucleon exchange is responsible for an additional term in the atomic Hamiltonian, conveniently written in the non-relativistic limit as:

$$V_{pv} = \frac{Q_W G_F}{4\sqrt{2}} \delta^3(r_e) \frac{\sigma_e \cdot p_e}{m_e c} + \text{H.C.}$$

In this expression the last factor is the axial-vector charge of the electron; the delta function results from the large mass of the Z_0, hence the short range of the interaction, causing effects in atoms to be so small; G_F is the Fermi constant and Q_W plays the same role as the nuclear electric charge in the Coulomb interaction: we called it the weak charge of the nucleus. It is the sum of the weak charges of all the constituents. This is the first electroweak parameter that APV experiments searched for. All of them rely on the measurement of the E_1^{pv} amplitude of a transition not allowed by EM interactions alone. The magnitude E_1^{pv} depends not only on Q_W but also on an atomic factor involving the atomic wave functions at the nucleus where V_{pv} contributes, but also outside the core where the coupling with the radiation field takes place. Therefore, an atomic physics calculation is necessary to extract Q_W from E_1^{pv}, which leads to a second source of uncertainty on Q_W^{ex} (see M. Safronova, this conference). In addition, we have to stress that this is the magnitude of E_1^{pv} which has to be theoretically interpreted, while the quantity measured by the Stark interference method is actually the asymmetry $A_{LR} = E_1^{pv}/\beta E$, βE being the amplitude induced by the applied electric field E. The uncertainties in both β and E are difficult to guarantee to better than 1%. For Cs, we have proposed [7] to rely on one contribution to the magnetic dipole transition amplitude M_1^{hf}, much more precisely known ($\sim 0.1\%$) on theoretical grounds, which can be isolated experimentally without ambiguity. Thus, by supplementing the measurement of A_{LR} by a measurement of $M_1^{hf}/\beta E$, one can achieve absolute calibration of E_1^{pv} exceeding 1% accuracy.

The most accurate experiment in cesium is that of the Boulder group [8]. It results from measurements of E_1^{pv}/β performed on the two hyperfine $\Delta F = \pm 1$ lines, combined together for eliminating the nuclear-spin dependent contribution, and from the measurement of M_1^{hf}/β made as advocated before. Once Q_W^{ex} was extracted, the authors claimed 0.35% and 0.4% experimental and theoretical uncertainty. They used the atomic theory available at that time and they concluded there was a deviation of Q_W^{ex} from the SM prediction Q_W^{th} by 2.6 σ. This result, published in 1999, prompted several theorists to reconsider the problem. A review of the abundant theoretical work which followed, can be found in A. Derevianko's publication [9], which also reports on an important improvement in the many body calculation (actually a real *tour de force*) leading to a final theoretical uncertainty of only 0.27%, hence smaller than the experimental one, with a readjustment of the central value of similar size. The implications of this new result $Q_W^{ex} = -73.16(29)_{ex}(20)_{th}$, are best illustrated by fig. 2, borrowed from [10] and updated to show the domains allowed by both atomic physics measurements and PVES ones in 2007, either with or without the modification resulting from [9]. The present agreement with the SM model is conspicuous. There are two consequences. 1) Since the existence of an additional neutral gauge boson would alter the value of Q_W^{ex} in a way depending on its mass, one can place a new limit on the mass of such an additional Z' boson of $M > 1.3\,\text{TeV}$, which (in the frame of SO_{10} unification) turns out to be even higher than the limit obtained from a direct search persued at the Tevatron collider (0.82 TeV). 2) Using the new Q_W^{ex} result one arrives at a determination of $\sin^2\theta^{eff} = 0.2381(11)$, now agreeing with the SM, which is slightly more precise than the previously most precise low-energy test performed in the Moeller e-scattering experiment at SLAC, fig. 2.

Present knowledge about the *nuclear-spin contribution* is quite limited: there is one sole result deduced from the same Boulder experiment, in this case by comparing to 1 the ratio r_{hf} of the E_1^{pv} amplitudes measured on the two $\Delta F = \pm 1$ hyperfine lines. It includes three effects: the "anapole moment", the nucleon-axial contribution to the electroweak e-nucleon interaction, and the perturbation of the nuclear-spin independent PV effect by the hyperfine interaction. The result obtained, $r_{hf} - 1 = (4.9 \pm 0.7) \times 10^{-2}$

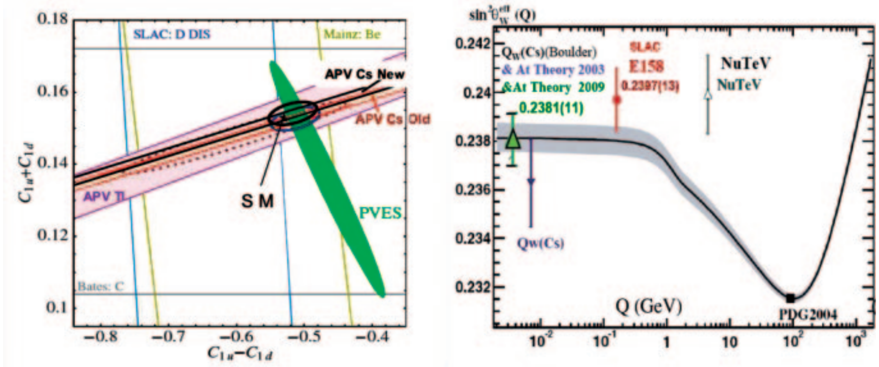

Fig. 2. – Left: Regions allowed by APV and PVES measurements for the weak charges of the quarks at 1σ. The black contour (95% CL) indicates the full constraint imposed by combining the results. The new Atomic Physics calculation [9] pushes the Cs band and the black contour slightly upward. The star indicates the SM prediction. (The red dotted ellipse is the full constraint anterior to PVES analysis.) Adapted from [10], with Cs band redrawn according to [9]. Right: Running of the electroweak coupling at low energies. Adapted from [11].

is actually very puzzling, since the theoretical prediction [12] is $(1.6 \pm 0.3) \times 10^{-2}$. In addition, no such effect was observed in Tl in spite of the 1% level of accuracy achieved.

Finally, the recent observation of APV in Yb [13] has opened the route to a new experimental approach. This atom has 7 stable isotopes and it should be possible to measure the ratios of E_1^{pv} for several of them. This makes it possible to eliminate the atomic factor in the ratio and thus have access to Q_W isotopic effects for the first time, see D. Budker, this conference.

Today, there still remain very important goals to be achieved.

1) 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 experiment (2.6% accurate) [14] was stopped by the powers that be, while its accuracy was still improving. Its principle is to take advantage of PV asymmetry amplification when a probe beam propagates through the vapor. Based on the experience acquired, we have suggested a different E-field configuration giving rise to a much larger PV asymmetry amplification and higher accuracy [15]. Another approach is to devise feasible experiments in francium and go ahead on the Ra^+ experiment. In both cases the effect is 20 times larger but atoms are scarce. One may expect that atomic calculations (M. Safronova, this conference) and experiments (S. Aubin and L. Willmann, this conference) will achieve an accuracy comparable to that obtained today in Cs.

2) Design an experiment specifically sensitive to the nuclear spin-dependent PV effect, *i.e.* where its contribution dominates that of Q_W, for solving the puzzle raised by the Cs result. (For proposals, see sect. **3**, and D. Budker and S. Cahn, this conference.)

3) Make precise measurements of E_1^{pv} ratios for different Yb isotopes, to observe isotopic effects on Q_W and possibly detect the anapole moments in the odd isotopes.

3. – Prospects for APV measurements using matter-wave interferometry

Let me now suggest new strategies for making APV measurements, inspired by the huge progress made in time and frequency metrology, over the past ten years. The field has been boosted by exploiting the methods of atom-interferometry, well-known for

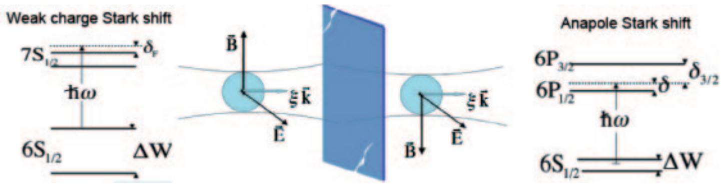

Fig. 3. – Two dressed atoms of opposite handedness display opposite linear Stark shifts.

unprecedented accuracy. However, a conceptual difficulty arises: metrologists are used to measuring energy differences or frequency shifts, while all APV measurements so far have been based on L-R asymmetries in the transition rates because there is no frequency shift associated with the PV transition dipole. An electric dipole, if P-odd and T-even, cannot give rise to a frequency shift in a stationnary atomic state perturbed by homogeneous E and B dc fields [16]. This difficulty can be solved by using light shifts [17].

When alkali atoms submitted to static electric and magnetic fields ($\vec{E}$, $\vec{B}$) are placed in a radiation field quasi-resonant with an atomic transition, a static electric dipole moment (EDM) can appear, hence also a linear Stark shift arising from V^{pv}. For a circularly-polarized radiation field the signature of the shift is given by the pseudoscalar T-even quantity $\chi = \vec{E} \wedge \xi\hat{k} \cdot B$, where ξ denotes the field helicity and $\xi\hat{k}$ the photon angular momentum. The mixed product specifies the handedness of the field configuration. There are actually two kinds of linear Stark shifts, depending on the light frequency. If the dressing beam is detuned with respect to the highly forbidden transition, the linear Stark shift involves the nuclear weak charge. In the case of a detuning with respect to the resonance transition (*e.g.* $6S_{1/2}$–$6P_{1/2}$ in Cs), the shift is largely dominated by the nuclear-spin dependent PV effect. In both cases we have shown that dressed alkali atoms can thus be artificially endowed with handedness [17]. Two atoms of opposite handedness (fig. 3) behave similarly to enantiomer molecules [18]. The handedness of the field configuration plays the same role as that of the chemical site inside an enantiomer molecule. For two mirror-image atoms one expects opposite shifts, just like for mirror-image molecules. However, there is a price to be paid: when the ground-state is admixed with the excited state by the dressing beam, the cold atom cloud acquires a certain decay time. One must ensure that over the time interval needed for observing the linear Stark

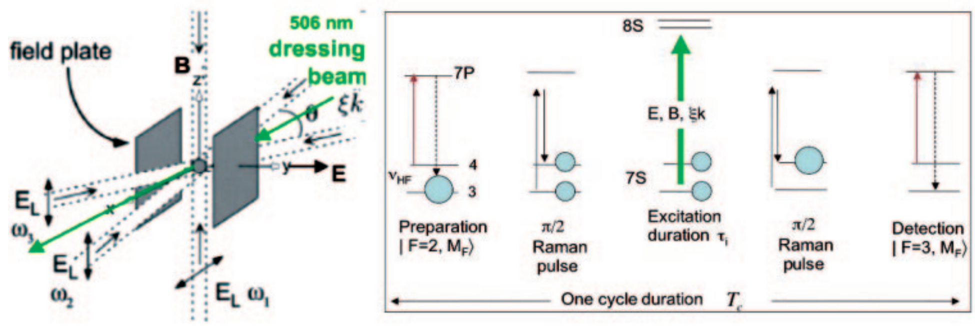

Fig. 4. – Left: Scheme for a PV Stark shift measurement inspired by a planned EDM project (Adapted from [19].) Right: Sequence of measurement for Fr atoms. (Courtesy of M. D. Plimmer.)

shift of the hyperfine or Zeeman transition frequencies, the dressed ground state decay can be neglected. Therefore, the dressing beam intensity, its detuning and the electric field magnitude have to fulfil compromises discussed in [17].

We illustrate our proposal basing on the design of a planned search for a static T-odd EDM shift, with state-of-the-art methods of atomic interferometry [19], fig. 4. We assume an interaction time $\tau_i = 1\,\mathrm{s}$ and a cycling time of 2 s. For ^{221}Fr, $I = 5/2$, we predict a weak-charge Stark shift of 100 μHz for a dressing beam intensity of 10 kW/cm^2, $E \approx$200 V/cm, detuning $\delta_F/2\pi \approx 130$ MHz. Measurements have to be performed in combination with parameter reversal and calibration sequences. The light shift and intensity noise from the dressing beam can be eliminated. For a sample of $N_{at} = 10^6$ cold Fr atoms, in conditions of projection-noise limited sensitivity, the signal to noise ($\propto \sqrt{N_{at}\,t}$) reaches 30 after a one hour averaging time, t. In the case of the anapole Stark shift, since the dressing beam is detuned from an allowed transition, the stability condition no longer involves the magnitude of E, which can therefore be made as large as possible. With the design of fig. 4, the same dressing beam intensity, E=100 kV/cm and optimized detuning (fig. 3), one expects an anapole Stark shift $\sim 400\,\mu$Hz for Fr ($\sim$10 times less for Cs).

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