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Can a stray static electric field mimic parity violation in Stark experiments on forbidden M_1 transitions ?

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Résumé. — Ce papier traite d'un aspect du problème des erreurs systématiques dans les expériences destinées à tester la violation de la parité dans les transitions radiatives M_1 interdites (telles que $nS_{1/2}-n'S_{1/2}$ du Cs ou $nP_{1/2}-n'P_{1/2}$ du Tl). Un signal parasite peut résulter de la présence d'un champ statique électrique ΔE qui ne se renverse pas avec la tension appliquée sur les électrodes. Dans le cas des expériences en cours une fausse asymétrie ne peut apparaître que sous l'effet combiné de ce champ parasite et d'un défaut d'alignement géométrique du montage. Nous présentons différentes méthodes utilisant les atomes eux-mêmes comme sonde pour tester la grandeur de ΔE et du défaut d'alignement ainsi que pour en effectuer une compensation partielle. Moyennant ces précautions il semble possible de maintenir l'effet systématique bien en dessous de 10 % du signal attendu.

Abstract. — This paper deals with one aspect of the problem of systematic errors in experiments designed to test parity violation in forbidden M_1 radiative transitions (e.g. $nS_{1/2}-n'S_{1/2}$ in Cs or $nP_{1/2}-n'P_{1/2}$ in Tl). A spurious signal can arise in presence of a stray static electric field ΔE which does not reverse with the voltage applied to the electrodes. For the experiments in progress the false asymmetry can only appear under the combined effect of this spurious field and of a geometrical misalignment of the set-up. We describe different procedure, using the atoms themselves as a probe, to test the magnitude of ΔE and of the misalignment, and to partially compensate these defects. Once such care is taken it seems to be possible to keep the systematics well below 10 % of the expected signal.

The problem of parity violation in neutral current interactions has motivated a new experimental field in view of testing in atoms the possible existence of small right-left asymmetries [1-5]. In such experiments special attention has to be paid to the validity of different criteria used to discriminate the signal under search against possible spurious effects. In the experiments performed in a d.c. electric field on forbidden magnetic one-photon transitions in monovalent heavy atoms, emphasis has been put on the many characteristic features which can contribute to give a well defined signature to a genuine effect [2]. The experiments on cesium [2] and thallium [3] involve the observation of an interference effect between the electric dipole amplitude E_1^{PV} due to the parity violating (PV) neutral currents, and the electric dipole amplitude E_1^{ind} induced by the static electric field E_0 : therefore the effect is odd with respect to E_0 . This feature allows the PV signal to be extracted by E_0 -reversal. However in practical conditions E_0 -reversal is always imperfect to some extent: reversal of the applied voltage actually changes the field from

$$E_0 + \Delta E \quad \text{to} \quad -E_0 + \Delta E$$

(ΔE can be thought of as a spurious field of arbitrary direction). Here we are concerned with the *false asymmetry associated with ΔE* . First we consider the experiments presently near completion on cesium [2] and thallium [3], in zero magnetic field, and evaluate its magnitude in terms of ΔE . Then we describe an experimental procedure allowing to control ΔE during the course of an experimental run, with the atoms themselves serving as a probe and we give a preliminary result obtained for our cesium experiment.

In the $H = 0$ parity violation experiment, Cs atoms are submitted to a d.c. electric field E_0 along Oy and excited by a circularly polarized laser beam, tuned for the forbidden transition and directed along Oz (see Fig. 1). The electronic polarization P_e of the excited state is monitored in a direction $\hat{k}_f$ along Ox. The predicted parity violation should appear as a small change of $P_e \cdot \hat{k}_f$ when the circular polarization of the incident beam is reversed. In order to examine possible defects with respect to this ideal situation, let us first introduce the formalism suitable for describing resonant absorption in the case of a forbidden M_1 transition ($S_{1/2}-S_{1/2}$ or $P_{1/2}-P_{1/2}$) in a d.c. electric field E of arbitrary direction. For an incident photon

Fig. 1. — The « ideal » geometrical configuration for a PV Stark experiment on an M_1 forbidden transition.

of momentum $\hat{\mathbf{k}}_i$ and (complex) polarization ε , the transition amplitude for a one valence electron atom can be obtained from an effective transition matrix T acting only on the electron angular momentum space [6] :

$$T = a \mathbb{1} + \mathbf{b} \cdot \boldsymbol{\sigma}; \quad (1.a)$$

here $a = \alpha \varepsilon \cdot \mathbf{E}$ is the Stark-induced electric dipole contribution associated with the scalar polarizability α ; the components of $\boldsymbol{\sigma}$ are the Pauli matrices, and

$$\mathbf{b} = i\beta \mathbf{E} \wedge \varepsilon - M_1 \hat{\mathbf{k}}_i \wedge \varepsilon + i \operatorname{Im} E_1^{\text{PV}} \varepsilon, \quad (1.b)$$

where $\hat{\mathbf{k}}_i$ is the unit vector of the propagation direction of the beam. Three contributions appear : the first one comes from the Stark-induced electric dipole, but now through the vector part β of the polarizability tensor ; the other two arise from the magnetic dipole and the parity violating electric dipole respectively. Explicit expressions of α , β and E_1^{PV} can be found in reference [6]. The ratio α/β has been found experi-

mentally equal to -8.8 for the $6S_{1/2}$ - $7S_{1/2}$ transition of Cs [2] and 1.23 for the $6P_{1/2}$ - $7P_{1/2}$ transition of Tl [3].

In the case where the laser selects one hyperfine component $F \rightarrow F'$ the electronic polarization $\mathbf{P}_e$ in the upper state F' can be deduced from the density matrix

$$\rho = P_{F'} T P_F T^\dagger P_{F'} \quad (2)$$

where $P_F = \sum_{m_F} |F, m_F\rangle \langle F, m_F|$ is the projection operator on the hyperfine level $F = I \pm 1/2$; thus

$$\mathbf{P}_e = \operatorname{Tr} \rho \boldsymbol{\sigma} / \operatorname{Tr} \rho. \quad (3)$$

In the case of circularly polarized incident light (photon helicity $\xi_i = +1$ or -1) we thus derive :

$$\mathbf{P}_e = \mathbf{P}_e^{(1)} + \mathbf{P}_e^{\text{PV}} + \mathbf{P}_e^{(2)} \quad (4.a)$$

with, for a $\Delta F = 0$ hyperfine transition :

$$\begin{aligned} \mathbf{P}_e^{(1)} &= 2 a_0(F) \frac{M_1}{\alpha E} \hat{\mathbf{E}} \wedge \hat{\mathbf{k}}_i; \\ \mathbf{P}_e^{\text{PV}} &= 2 a_0(F) \xi_i \frac{\operatorname{Im} E_1^{\text{PV}}}{\alpha E} \hat{\mathbf{E}} \wedge \hat{\mathbf{k}}_i \end{aligned} \quad (4.b)$$

and, for a $\Delta F = 1$ transition from state $(n, J = 1/2, 2I - F')$ to state $(n', J = 1/2, F')$:

$$\begin{aligned} \mathbf{P}_e^{(1)} &= 2 a_1(F') \frac{M_1}{\beta E} \hat{\mathbf{E}} \wedge \hat{\mathbf{k}}_i; \\ \mathbf{P}_e^{\text{PV}} &= 2 a_1(F') \xi_i \frac{\operatorname{Im} E_1^{\text{PV}}}{\beta E} \hat{\mathbf{E}} \wedge \hat{\mathbf{k}}_i. \end{aligned} \quad (4.c)$$

$\mathbf{P}_e^{(2)}$ orthogonal to $\hat{\mathbf{E}} \wedge \hat{\mathbf{k}}_i$ involves only Stark amplitudes and will be explicitated below ; explicit expressions of $a_0(F)$ and $a_1(F)$ are :

$$a_0(F) = \frac{1}{3} (1 + 2 g_F) \left(1 + g_F \frac{\beta}{\alpha} \right) \left\{ |\hat{\mathbf{E}} \wedge \hat{\mathbf{k}}_i|^2 + \frac{1 + 2 g_F}{3} \frac{\beta^2}{\alpha^2} (|\hat{\mathbf{E}} \wedge \hat{\mathbf{k}}_i|^2 + 2 |\hat{\mathbf{E}} \cdot \hat{\mathbf{k}}_i|^2) \right\}^{-1} \quad (4.d)$$

$$a_1(F) = \frac{1}{2} (1 + 2 g_F) \{ |\hat{\mathbf{E}} \wedge \hat{\mathbf{k}}_i|^2 + 2 |\hat{\mathbf{E}} \cdot \hat{\mathbf{k}}_i|^2 \}^{-1}. \quad (4.e)$$

Here $\hat{\mathbf{E}} = \mathbf{E}/|\mathbf{E}|$ is the unit vector of the (arbitrary) direction of $\mathbf{E}$, and $g_F = (F - I)/(I + 1/2)$; eqs. (4) are valid under the assumption $\alpha E, \beta E \gg M_1, \operatorname{Im} E_1^{\text{PV}}$.

In eq. (4.a) we recognize the three contributions to the electronic polarization already discussed in previous papers [2, 6]. The component $\mathbf{P}_e^{(1)} + \mathbf{P}_e^{\text{PV}}$ along $\hat{\mathbf{k}}_i \wedge \hat{\mathbf{E}}$ results from the interference between the mixed $M_1 - E_1^{\text{PV}}$ amplitude and the Stark amplitude. Note the presence of ξ_i (a T -invariant pseudoscalar) in front of $\operatorname{Im} E_1^{\text{PV}}$: while M_1 brings an axial contribution to the angular momentum $\mathbf{P}_e$, E_1^{PV} appears in a

vector one, which is a clear indication that the atomic hamiltonian contains a P -odd T -even piece : this contribution generates the PV signal $\mathbf{P}_e^{\text{PV}} \cdot \hat{\mathbf{k}}_i$.

We now turn to the component of the electronic polarization $\mathbf{P}_e^{(2)}$, for a $\Delta F = 0$ transition :

$$\begin{aligned} \mathbf{P}_e^{(2)} &= a_0(F) \times \\ &\times \left[-2 \frac{\beta}{\alpha} \xi_i \hat{\mathbf{k}}_i \left(1 + g_F \frac{\beta}{\alpha} \right)^{-1} + 2 \frac{\beta}{\alpha} \xi_i (\hat{\mathbf{E}} \cdot \hat{\mathbf{k}}_i) \hat{\mathbf{E}} \right] \end{aligned} \quad (5.a)$$

and for a $2I - F' \rightarrow F'$ transition :

$$\mathbf{P}_e^{(2)} = 2 a_1(F') \xi_i(\hat{\mathbf{E}} \cdot \hat{\mathbf{k}}_i) \hat{\mathbf{E}}. \quad (5.b)$$

Although this does not appear obviously on eqs. (5) there are two contributions in $\mathbf{P}_e^{(2)}$:

- i) an interference effect between the two Stark amplitudes αE and βE (associated with scalar and vector polarizabilities) and
- ii) the direct excitation associated with the vector Stark amplitude βE .

The α - β interference exists only for $\Delta F = 0$ transitions since the scalar operator $\alpha E_0 \mathbb{1}$ cannot connect two states having a different total angular momentum

The PV polarization $\mathbf{P}_e^{\text{PV}}$ can in principle be discriminated against $\mathbf{P}_e^{(1)}$ and $\mathbf{P}_e^{(2)}$ owing to its behaviour under :

- i) E-reversal ($\mathbf{P}_e^{\text{PV}}$ and $\mathbf{P}_e^{(1)}$ are odd, $\mathbf{P}_e^{(2)}$ is even) ;
- ii) ξ_i -reversal ($\mathbf{P}_e^{\text{PV}}$ and $\mathbf{P}_e^{(2)}$ are odd, $\mathbf{P}_e^{(1)}$ is even) ;
- iii) reflection of the laser beam backwards, which reverses both ξ_i and $\hat{\mathbf{k}}_i$ ($\mathbf{P}_e^{\text{PV}}$ and $\mathbf{P}_e^{(2)}$ are even, $\mathbf{P}_e^{(1)}$ is odd). In addition, $\mathbf{P}_e^{\text{PV}}$ (like $\mathbf{P}_e^{(1)}$) is created along $\hat{\mathbf{E}} \wedge \hat{\mathbf{k}}_i$, while $\mathbf{P}_e^{(2)}$ is created in the $(\hat{\mathbf{E}}, \hat{\mathbf{k}}_i)$ plane normal to $\hat{\mathbf{E}} \wedge \hat{\mathbf{k}}_i$.

However it is important to check how this discrimination is affected by possible experimental imperfections in reversals and alignments. In the present paper we restrict ourselves to imperfect E-reversal : we assume that voltage reversal changes the field from $-\mathbf{E}_0 + \Delta\mathbf{E}$ to $+\mathbf{E}_0 + \Delta\mathbf{E}$. The point is that if $\mathbf{E}_0$ is not quite orthogonal to both $\hat{\mathbf{k}}_i$ and $\hat{\mathbf{k}}_f$, then the contribution $\xi_i(\hat{\mathbf{E}} \cdot \hat{\mathbf{k}}_i) \hat{\mathbf{E}}$ in eq. (5), which behaves like $\mathbf{P}_e^{\text{PV}}$ under reversals ii) and iii), will look partially odd under *voltage* reversal and mimic a PV signal (unless it is zero (if $\hat{\mathbf{E}}_0 \cdot \hat{\mathbf{k}}_i = 0$) or undetected

$$(\hat{\mathbf{E}}_0 \cdot \hat{\mathbf{k}}_f = 0)).$$

On the other hand the $\hat{\mathbf{k}}_i$ component in eq. (5.a) will bring no trouble since it does not depend on $\mathbf{E}$ (neither in magnitude nor in direction).

Let us replace $\mathbf{E}$ by $\eta \hat{\mathbf{E}}_0 + \Delta\mathbf{E}$ ($\eta = \pm 1$) in eqs. (4) and (5), and work out the part of $\mathbf{P}_e^{(2)}$ that is odd in η . Since $|\Delta\mathbf{E}| \ll |\mathbf{E}_0|$, we shall develop to first order in $|\Delta\mathbf{E}|/|\mathbf{E}_0|$. In addition, since in the considered experiment the three directions $\hat{\mathbf{E}}_0$, $\hat{\mathbf{k}}_i$, $\hat{\mathbf{k}}_f$ are mutually orthogonal within small misalignments, each coefficient of this development will be expressed only to the lowest non-vanishing order (which turns out to be the first) with respect to $\hat{\mathbf{E}}_0 \cdot \hat{\mathbf{k}}_i$, $\hat{\mathbf{E}}_0 \cdot \hat{\mathbf{k}}_f$ and $\hat{\mathbf{k}}_i \cdot \hat{\mathbf{k}}_f$. We thus obtain :

$$\begin{aligned} \mathbf{P}_{e\text{odd}}^{(2)} &= (\mathbf{P}_e^{\text{PV}} \cdot \hat{\mathbf{k}}_f) \times \\ &\times \left[(\hat{\mathbf{E}}_0 \cdot \hat{\mathbf{k}}_i) \frac{\beta \Delta\mathbf{E}_\perp}{\text{Im } E_1^{\text{PV}}} + \left(\frac{\beta \Delta\mathbf{E}}{\text{Im } E_1^{\text{PV}}} \cdot \hat{\mathbf{k}}_i \right) \hat{\mathbf{E}}_0 \right], \quad (6.a) \end{aligned}$$

expression valid for any hyperfine transition, $\Delta\mathbf{E}_\perp$ denoting the component of $\Delta\mathbf{E}$ normal to $\mathbf{E}_0$. The

spurious signal is given by the component of $\mathbf{P}_e^{(2)}_{\text{odd}}$ in the direction of observation $\hat{\mathbf{k}}_f$, namely :

$$\begin{aligned} \mathbf{P}_{e\text{odd}}^{(2)} \cdot \hat{\mathbf{k}}_f &= (\mathbf{P}_e^{\text{PV}} \cdot \hat{\mathbf{k}}_f) \left[(\hat{\mathbf{E}}_0 \cdot \hat{\mathbf{k}}_i) \left(\frac{\beta \Delta\mathbf{E}}{\text{Im } E_1^{\text{PV}}} \cdot \hat{\mathbf{k}}_f \right) + \right. \\ &\left. + \left(\frac{\beta \Delta\mathbf{E}}{\text{Im } E_1^{\text{PV}}} \cdot \hat{\mathbf{k}}_i \right) (\hat{\mathbf{E}}_0 \cdot \hat{\mathbf{k}}_f) \right]. \quad (6.b) \end{aligned}$$

We have expressed it here in terms of the « true effect » $\mathbf{P}_e^{\text{PV}} \cdot \hat{\mathbf{k}}_f$. We see that the expression between brackets involves the product of misalignment angles $\hat{\mathbf{E}}_0 \cdot \hat{\mathbf{k}}_i$ and $\hat{\mathbf{E}}_0 \cdot \hat{\mathbf{k}}_f$ by the unreversed (spurious) d.c. field components *normal* to $\mathbf{E}_0$: this means that a small change of the *modulus* of the field without a change of direction has no effect. Two remarkable features of the result are

- i) that it is independent on the *magnitude* of the electric field in which the experiment is done, and
- ii) that the only involved parameter of the transition is the ratio of the vector polarizability to the parity violating dipole amplitude. Inspection of this ratio for Cs ($6S_{1/2} - 7S_{1/2}$ [6]) and for Tl ($6P_{1/2} - 7P_{1/2}$ [7])

$$\frac{\beta}{\text{Im } E_1^{\text{PV}}}_{\text{Cs}} = 0.6 \times 10^3 \text{ V}^{-1} \times \text{cm};$$

$$\frac{\beta}{\text{Im } E_1^{\text{PV}}}_{\text{Tl}} = 0.7 \times 10^3 \text{ V}^{-1} \times \text{cm}$$

shows that they are nearly equal : the larger E_1^{PV} amplitude of Tl (due to the Z^3 -increase [1]) being compensated by its larger vector polarizability (due to a larger spin-orbit interaction). This means that the field $\Delta\mathbf{E}$ able to simulate the effect under search is in both cases of the order of $\chi^{-1} \times 2 \times 10^{-3} \text{ V/cm}$. Here the misalignment angle χ is likely to be in the range of 10^{-1} to 10^{-2} rad., in absence of special control. If one wants to reduce the systematic asymmetry to a level lower than 10 % of the effects under search is then appears necessary to control whether the spurious field components $\Delta\mathbf{E} \cdot \hat{\mathbf{k}}_i$ and $\Delta\mathbf{E} \cdot \hat{\mathbf{k}}_f$ do not exceed a few millivolts per cm during the experiment. Let us remark that the same problem is also present in hydrogen PV experiments in progress, but at a much more acute level, since the tolerable limit of stray electric fields is smaller by several orders of magnitude [5].

In the Cs experiment, atoms situated between the capacitor plates are relatively well insulated from outer static fields, because of electric shielding by the thick earth-connected metallic oven, by the partially conducting Cs vapour and by the plates themselves. A more worrying cause of defect might be surface impurities on the (yet carefully cleaned and outgassed) stainless steel capacitor plates; the resulting field non-uniformities, differently screened by the space charge when the voltage has one or the other sign, would have to be averaged over the observation

volume. In view of the difficulty of estimating a reliable value for $\Delta\mathbf{E}_\perp$, we arrive at the conclusion that the only convincing way to control $\Delta\mathbf{E} \cdot \hat{\mathbf{k}}_i$ and $\Delta\mathbf{E} \cdot \hat{\mathbf{k}}_f$ is to use the atoms themselves as a probe during the experimental run. So we looked for other physical observables manifesting directly the existence of $\Delta\mathbf{E} \cdot \hat{\mathbf{k}}_f$ or $\Delta\mathbf{E} \cdot \hat{\mathbf{k}}_i$: thus we have been led to proceed along the following lines for controlling separately each of the two terms in eq. (6.b):

1. Control of $(\Delta\mathbf{E} \cdot \hat{\mathbf{k}}_f)(\hat{\mathbf{E}}_0 \cdot \hat{\mathbf{k}}_i)$. — Our procedure for controlling $\Delta\mathbf{E} \cdot \hat{\mathbf{k}}_f$, first, is based on the fact that the upper state population, just like $\mathbf{P}_e^{(2)}$, is a quadratic function of $\mathbf{E}$ and can acquire a small odd contribution under unrigorous field reversal. The upper state population $\text{Tr } \rho$ can be expressed (cf. eqs. (2), (1.a) and (1.b)) as a linear combination of $\alpha^2 |\mathbf{E} \cdot \boldsymbol{\varepsilon}|^2$ and $\beta^2 |\mathbf{E} \wedge \boldsymbol{\varepsilon}|^2$. Just like previously we replace $\mathbf{E}$ by $\eta\mathbf{E}_0 + \Delta\mathbf{E}$ and develop to first order in $|\Delta\mathbf{E}|/|\mathbf{E}_0|$, expressing the coefficients only to the lowest non-vanishing order (which, here, turns out to be the zeroth) in $(\hat{\mathbf{E}}_0 \cdot \hat{\mathbf{k}}_i)$, $(\hat{\mathbf{E}}_0 \cdot \hat{\mathbf{k}}_f)$ and $(\hat{\mathbf{k}}_i \cdot \hat{\mathbf{k}}_f)$. The η -odd contributions are thus found to be:

$$\begin{aligned} |\hat{\mathbf{E}} \cdot \boldsymbol{\varepsilon}|_{\text{odd}}^2 &= 2 E_0 (\Delta\mathbf{E} \cdot \hat{\mathbf{k}}_f) \text{Re}(\varepsilon_y^* \varepsilon_x) + \\ &\quad + 2(\Delta\mathbf{E} \cdot \mathbf{E}_0) |\varepsilon_y|^2, \\ |\mathbf{E} \wedge \boldsymbol{\varepsilon}|_{\text{odd}}^2 &= -2 E_0 (\Delta\mathbf{E} \cdot \hat{\mathbf{k}}_f) \text{Re}(\varepsilon_y^* \varepsilon_x) + \\ &\quad + 2(\Delta\mathbf{E} \cdot \mathbf{E}_0) |\varepsilon_x|^2. \end{aligned} \quad (7)$$

As a result the part of the upper state population that is odd under voltage reversal contains two contributions: one is proportional to the product of $(\Delta\mathbf{E} \cdot \hat{\mathbf{k}}_f)$ times the linear polarization ratio $2 \text{Re}(\varepsilon_y^* \varepsilon_x)$ along axes oriented at 45° with respect to Ox and Oy ; the second one is proportional to $(\Delta\mathbf{E} \cdot \mathbf{E}_0)$ and depends only on the linear polarization along Ox and Oy themselves. Thus the quantity $(\Delta\mathbf{E} \cdot \hat{\mathbf{k}}_f)$ can be extracted by measuring the component of the upper state population that is reversed either under voltage reversal or when the plane polarization of the laser beam is switched from -45° to 45° with respect to $\mathbf{E}_0$.

We have actually performed this control in our cesium experiment: we monitor the upper state population through the fluorescence light intensity associated with the $7S_{1/2}$ - $6P_{1/2}$ decay. The polarization of the laser beam is initially linear orthogonal to $\mathbf{E}_0$. The beam then passes through a Pockels modulator with axes at 45° with respect to $\mathbf{E}_0$. In the search for parity violation the retardation is modulated symmetrically about zero at some frequency ω : on the transmitted beam the circular polarization ratio $2 \text{Im}(\varepsilon_x^* \varepsilon_y)$ is then modulated at frequency ω , while the linear polarization ratio $|\varepsilon_x|^2 - |\varepsilon_y|^2$ along Ox , Oy is modulated at frequency 2ω and the linear polarization ratio $2 \text{Re}(\varepsilon_x^* \varepsilon_y)$ at 45° with respect to Ox , Oy is identically zero. For the measurement of $\Delta\mathbf{E} \cdot \hat{\mathbf{k}}_f$ we simply insert after the Pockels modulator a quarterwave plate with axes parallel and perpendi-

cular to $\mathbf{E}_0$: this just exchanges the properties of the circular polarization ratio $2 \text{Im}(\varepsilon_x^* \varepsilon_y)$, and of the linear one, $2 \text{Re}(\varepsilon_x^* \varepsilon_y)$, while the properties of the xy polarization ratio remain unchanged: $\Delta\mathbf{E} \cdot \hat{\mathbf{k}}_f$ is then obtained from the voltage-odd component in the modulation amplitude at frequency ω . The result of this measurement was that no effect came out from noise so far. So we can only give an upper limit for the spurious field component:

$$\Delta\mathbf{E} \cdot \hat{\mathbf{k}}_f < 7 \times 10^{-3} \text{ V/cm}$$

(to one standard deviation accuracy).

This preliminary result is quite encouraging, since geometrical controls (cathetometer aimings) performed on the set-up show the quantity $|\hat{\mathbf{E}}_0 \cdot \hat{\mathbf{k}}_i|$ to be less than 10^{-2} : thus the systematic error corresponding to the first term of eq. (6.b) is less than 5% of the expected PV signal.

2. Control of $(\Delta\mathbf{E} \cdot \hat{\mathbf{k}}_i)(\hat{\mathbf{E}}_0 \cdot \hat{\mathbf{k}}_f)$. — In our Cs experiment it is difficult to control by purely geometrical means the orthogonality of $\mathbf{E}_0$ and $\hat{\mathbf{k}}_f$ with an accuracy better than 10^{-1} radian. So at first sight the situation for this term might look less favourable (by a factor 10 roughly). However we show that this handicap can be overcome by probing the misalignment $(\hat{\mathbf{E}}_0 \cdot \hat{\mathbf{k}}_f)$ with the atoms themselves and by correcting its effect. It is then sufficient to test the component of $\Delta\mathbf{E}$ along $\hat{\mathbf{k}}_i$ with an accuracy comparable to that obtained for the component along $\hat{\mathbf{k}}_f$.

For easier understanding of what follows one should keep in mind that eqs. (4.a) to (6.b) give the atomic polarization in *zero magnetic field*; in the case of a non-zero magnetic field the stationary value of the polarization results from the competition (« Hanle effect ») between creation by the light wave and decay by Larmor precession and desexcitation; eqs. (4.a) to (6.b) then give only the *source term* for this process.

2.1 CONTROL OF $\Delta\mathbf{E} \cdot \hat{\mathbf{k}}_i$. — We use the $\hat{\mathbf{E}}_0$ component of $\mathbf{P}_e^{(2)}$ itself, (see eq. (6.a)):

$$(\mathbf{P}_e^{\text{PV}} \cdot \hat{\mathbf{k}}_f) \left(\frac{\beta \Delta\mathbf{E}}{\text{Im } E_1^{\text{PV}}} \cdot \hat{\mathbf{k}}_i \right) \hat{\mathbf{E}}_0. \quad (8)$$

By applying a magnetic field $\mathbf{H}$ along $\hat{\mathbf{k}}_i$, owing to Hanle effect this polarization can be brought in the direction of observation $\hat{\mathbf{k}}_f$; it can then be identified due to its oddness under $\mathbf{H}$ reversal as well as under voltage reversal. The role of $\mathbf{H}$ is twofold: it is used to identify the defect and to « amplify » it by a factor $(1/2)(\hat{\mathbf{E}}_0 \cdot \hat{\mathbf{k}}_f)^{-1} \gg 1$.

In this experiment, currently in preparation, we want to point out that $\Delta\mathbf{E} \cdot \hat{\mathbf{k}}_i$ can in principle be compensated as soon as it emerges from noise, owing to a small d.c. electric field deliberately applied along $\hat{\mathbf{k}}_i$ by means of suitable auxiliary electrodes. (These

should be located outside the capacitor plates, so as not to spoil the field $\mathbf{E}_0$ by electrical influence.)

2.2 CONTROL OF $\hat{\mathbf{E}}_0 \cdot \hat{\mathbf{k}}_f$. — The atoms are used to monitor this misalignment in the following way. An electric field $\mathbf{e}$ is applied along $\hat{\mathbf{k}}_i$, by means of the auxiliary electrodes just mentioned. The total electric field is now $\mathbf{E} = \mathbf{E}_0 + \mathbf{e}$. (The small defect $\Delta\mathbf{E}$ is irrelevant in what follows. Note : $\mathbf{e}$ is on only for this particular control ; it is then switched off for the PV experiment itself.) Substituting into eq. (5), we see that the atomic polarization acquires along $\mathbf{E}_0$ a contribution $\mathcal{P}_e$ that can be unambiguously discriminated due to its oddness *versus* each of the three parameters ξ_i , $\mathbf{e}$ and $\mathbf{E}_0$; the value of this contribution for a $F \rightarrow F'$ transition is :

$$\mathcal{P}_e = K(F, F') \cdot \xi_i \frac{e/E_0}{1 + e^2/E_0^2} \hat{\mathbf{E}}_0 \quad (9)$$

where $K(F, F') = 2 a_0(F) \cdot \beta/\alpha$ and

$$K(2I - F', F') = 2 a_1(F') .$$

The detected component $\mathcal{P}_e \cdot \hat{\mathbf{k}}_f$ of $\mathcal{P}_e$ is proportional to the misalignment angle $\hat{\mathbf{E}}_0 \cdot \hat{\mathbf{k}}_f$ we want to control. The factor involving e , whose value might be difficult to determine reliably, can be eliminated by applying a d.c. magnetic field along $\hat{\mathbf{k}}_i$ which rotates the atomic polarization (Hanle effect). The component of $\mathcal{P}_e$ in the direction of observation then becomes :

$$\mathcal{P}_e \cdot \hat{\mathbf{k}}_f = K(F, F') \xi_i \frac{e/E_0}{1 + e^2/E_0^2} \times \left[\frac{\hat{\mathbf{E}}_0 \cdot \hat{\mathbf{k}}_f}{1 + (H/\Delta H)^2} + \frac{H/\Delta H}{1 + (H/\Delta H)^2} \right], \quad (10)$$

where ΔH is the Hanle width. Since $\hat{\mathbf{E}}_0 \cdot \hat{\mathbf{k}}_f \ll 1$, we finally obtain

$$\hat{\mathbf{E}}_0 \cdot \hat{\mathbf{k}}_f = \frac{1}{2} (\mathcal{P}_{e, H=0} \cdot \hat{\mathbf{k}}_f) / (\mathcal{P}_{e, H=\Delta H} \cdot \hat{\mathbf{k}}_f) .$$

Note that the misalignment $\hat{\mathbf{E}}_0 \cdot \hat{\mathbf{k}}_f$ thus measured can be corrected following the same principle : owing to Hanle effect, applying along $\hat{\mathbf{k}}_i$ a small d.c. magnetic field of amplitude $h = -\Delta H(\hat{\mathbf{E}}_0 \cdot \hat{\mathbf{k}}_f)$ causes atomic polarizations created along $\mathbf{E}_0$ to become orthogonal to $\hat{\mathbf{k}}_f$ (see eq. (10)), thus escaping detection.

Once the above prescriptions are followed, we finally have all reasons to believe that, with the possible help of the two compensations, the second term of eq. (6.b) will stay smaller than the first one and well below 5 per cent of the expected PV signal. (A more precise limit to the systematics is likely to be extracted from data processing.)

To avoid misunderstanding about the physical origin of the systematic effect discussed in the present paper we would like to emphasize the following point : simulation of $\mathcal{P}_e^{\text{PV}}$ by $(\mathcal{P}_e^{(2)})_{\text{odd}}$ is not contradictory with the opposite space reflexion symmetries of the electromagnetic (Stark) and weak interactions. In the ideal case of perfect experimental geometry (and instruments) our experiment is designed so as to be sensitive only to an atomic polarization which is directed along $\hat{\mathbf{k}}_f$ in the xy plane and depends only on the electric field $\mathbf{E}_0 \parallel Oy$ and on the longitudinal angular momentum $\xi_i \mathbf{k}_i \parallel Oz$ of the laser wave. Thus, under a symmetry with respect to the xy plane, since $\hat{\mathbf{k}}_f$, $\mathbf{E}_0$ and $\xi_i \mathbf{k}_i$ are all conserved, so is also the detected polarization ; but since it lies *in* the xy plane, this detected polarization has to be either zero or *vector* instead of axial : i.e. the experiment is sensitive only to a *parity violating* effect. However, as soon as the geometry (or the instruments) is imperfect, this argument is no longer valid, and spurious parity-conserving signals may arise. In the case considered in this paper (see eq. (6)) the symmetry with respect to the xy plane is broken by a non-zero value either of $\hat{\mathbf{E}}_0 \cdot \hat{\mathbf{k}}_i$ or of $\Delta\mathbf{E} \cdot \hat{\mathbf{k}}_i$. However, since the space-time symmetries of the Stark and weak interactions remain different the simulation of $\mathcal{P}_e^{\text{PV}}$ by $(\mathcal{P}_e^{(2)})_{\text{odd}}$ is nothing but an artefact that has to be eliminated by sufficient experimental control of the type discussed in this paper.

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