Measuring the Fr Weak Nuclear Charge by Observing a Linear Stark Shift with Small Atomic Samples

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We study the chirality of ground-state alkali atoms in **E** and **B** fields, dressed with a circularly-polarized beam near-detuned ($\lesssim 1$ GHz) from an E-field-assisted forbidden transition such as $7S-8S$ in Fr. We predict parity violating energy shifts of their sublevels, linear in **E** and the weak nuclear charge Q_W. A dressing beam of 10 kW/cm^2 at 506 nm produces a shift of ~ 100 μHz at $E = 100$ V/cm, $B \gtrsim 50$ mG which should be observable with $\sim 10^4$ Fr atoms confined in an optical dipole trap. We discuss optimal conditions, parameter reversals, and a calibration procedure to measure Q_W.

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Atomic physics experiments in cesium have succeeded in determining the parity violating (PV) electric-dipole $6S-7S$ transition amplitude, $E_1^{\rm pv}$ as small as 0.8×10^{-11} ea_0, with a precision progressively [1] reaching 0.35%, once both experimental [2] and absolute calibration [3] uncertainties are included. Thanks to the *tour de force* made by atomic theorists [4], the weak Cs nuclear charge, Q_W, extracted from the result leads to a unique low-energy test of the standard electroweak theory. Strong incentives for still improving its precision, e.g., for reducing the limits on the mass of an eventual additional, light or heavy, neutral boson [5], motivate the present work.

A method taking advantage of the PV asymmetry amplification demonstrated in Cs [6] has been proposed [7]. However, as an alternative, there have been suggestions for PV measurements in radioactive francium [8], the heaviest of the alkalis. The reason is that $E_1^{\rm pv}(7S-8S)$ is expected to be 18 times larger than in Cs $(6S-7S)$ [4]. Several spectroscopic measurements have already been performed on cold Fr atoms inside a magneto optical trap (MOT), but even the observation of this forbidden transition still looks difficult. Contrary to Cs, the main hurdle is the small number of trapped atoms available: $\sim 10^4$ for continuous operation over many hours. This number will be hard to exceed, even though higher peak production has been reported [9]. The PV detection schemes, used in the past for observing left-right asymmetries in the Cs forbidden transition rates, involved from 10^7 to 10^{12} atoms. Transposition to Fr raises signal-to-noise ratio difficulties.

By contrast, frequency measurements based on atom interferometry have demonstrated unprecedented accuracy and proved to be well adapted to cold samples of 10^4 to 10^6 atoms. Therefore, the existence of a PV effect attainable by these methods could form the basis of a realistic Fr project. The problem is that an electric-dipole moment violating P but not T cannot give rise to a frequency shift in a stationary atomic system submitted only to homogeneous dc electric and magnetic fields, as stated by Sandars' theorem [10]. The strategy is to find some way around this restriction. The light-shift proposal for a single Ba$^+$ ion [11], based on the radiation field gradient in a standing wave, is made difficult by the need for precise adjustment of the ion position in this field. For the Cs nuclear anapole moment, we have suggested measuring the hyperfine (hf) linear Stark shift of the ground state dressed by a circularly polarized laser beam detuned from the first resonance line [12]. In this case, the measurement involves off-diagonal matrix elements of the PV electric dipole between hf ground states. No similar effect exists for the Q_W electric dipole since it does not connect hyperfine sublevels. In this Letter, we show that, for a suitable near-detuning of the dressing beam from the Stark-field-assisted $nS-n'S$ transition, an interferometric measurement of Q_W may also be achieved by observing a linear Stark shift.

We consider alkali atoms in their ground state, placed in crossed dc electric and magnetic fields, **E** and **B**, which interact with a laser beam of direction $\hat{k}$ orthogonal to both fields. Its angular frequency ω is detuned from the E-field assisted, $nS-n'S$ transition of frequency ω_0 by an amount $\delta = \omega - \omega_0$. Opposite parity states are mixed by the electric-dipole coupling $V_E = -\mathbf{D}\cdot\mathbf{E}$. A second mixing between $S_{1/2}$ and $P_{1/2}$ states results from the PV electron-nucleus interaction $V_{\rm pv}$, associated with the weak nuclear charge Q_W [1], $\langle n'P_{1/2}|V_{\rm pv}|nS_{1/2}\rangle = -iG_F Q_W \langle n'P_{1/2}|\mathcal{R}|nS_{1/2}\rangle$. The factor i results from its time reversal invariance, G_F is the Fermi constant, and $\mathcal{R}$ a short-range pseudoscalar operator mixing the $S_{1/2}$ and $P_{1/2}$ wave functions in the vicinity of the nucleus.

To describe the electric-dipole amplitudes induced by the radiation field as a result of both mixings, it is convenient to introduce the effective electric-dipole operator which behaves as a matrix element in the atom's radial coordinate space and as an operator in the spin space,

$$\mathbf{D}^{\rm ef}(n,n') = -\alpha(n,n')\mathbf{E} - i\beta(n,n')\vec{\sigma}\wedge\mathbf{E} - i{\rm Im}E_1^{\rm pv}(n,n')\vec{\sigma} + M_1\vec{\sigma}\wedge\mathbf{k}, \quad (1)$$

where $\vec{\sigma}$ is the Pauli matrix for the electron spin operator. The final term describes the effective contribution of the parity conserving (PC) magnetic dipole amplitude [1,13], in which, for both Cs and Fr, $M_1 \approx 2 \times 10^4 \mathrm{Im} E_1^{\mathrm{pv}}$.

We use the quantized form of the radiation field, involving the creation and annihilation operators $a^\dagger$ and a. The circularly polarized laser beam is described by a normalized N photon state $|N\rangle$ with energy density $\epsilon_0 \mathcal{E}^2 = N\hbar\omega/V$ localized inside a volume V. The Hamiltonian $V_{\mathrm{rad}} = -\sqrt{\frac{\hbar\omega}{2\epsilon_0 V}}[a\mathbf{e}(\xi)\cdot\mathbf{D} + \mathrm{H.c.}]$ describes the atom-field dipolar coupling with $\mathbf{e}(\xi) = \frac{1}{\sqrt{2}}(\mathbf{e}_1 + i\xi\mathbf{e}_2)$, $\mathbf{e}_i$ being two real orthogonal unit vectors normal to the direction $\hat{k}$ of the laser beam, and $\xi = \pm 1$ defining the helicity. For the combined atom-field initial and final states, $|\tilde{i}\rangle = |n\tilde{S}_{1/2}; F, m_F\rangle|N\rangle$ and $|\tilde{f}\rangle = |n'\tilde{S}_{1/2}; F', m'_F\rangle|N-1\rangle$, perturbed by $V_E + V_{\mathrm{pv}}$, the effective dipolar coupling writes $V_{\mathrm{rad}}^{\mathrm{ef}} = -\sqrt{\frac{\hbar\omega}{2\epsilon_0 V}}[a\mathbf{e}(\xi)\cdot\mathbf{D}^{\mathrm{ef}} + \mathrm{H.c.}]$; F, m_F are the hf and magnetic quantum numbers, $\hbar\Delta W$ is the nS hf splitting.

Using this approach, we derive the general expression of the nS state light shift [14] arising from virtual absorption and emission of near-detuned $nS_{1/2} - n'S_{1/2}$ photons by time-independent perturbation theory

$$\delta E = |\langle\tilde{i}|V_{\mathrm{rad}}^{\mathrm{ef}}|\tilde{f}\rangle|^2/\hbar\delta. \tag{2}$$

The fact that $V_{\mathrm{rad}}^{\mathrm{ef}}$ appears alone might imply that other contributions are missing. Indeed, in a rigorous perturbative treatment, one has to consider all fourth-order terms, linear in V_{pv}, V_E, and quadratic in V_{rad}. In fact, the only omitted terms are strongly nonresonant at the small detunings $\delta \lesssim \Delta W$ supposed here. Only for a dressing beam approaching the resonance line do they dominate, giving rise, then, to the anapole shift discussed in [12].

In expression (2), we find all the terms making up the operator $\mathbf{D}^{\mathrm{ef}}\cdot\mathbf{e}(\xi)$ with their Rabi frequencies, the two scalar ($q = \alpha$) and vector ($q = \beta$) Stark-induced ones, $\Omega_{\mathrm{ind}}^q = qE\mathcal{E}/\hbar\sqrt{2}$, in addition to the tiny parity violating one, $\Omega_{\mathrm{pv}} = \mathrm{Im}E_1^{\mathrm{pv}}\mathcal{E}/\hbar\sqrt{2}$ and the 2×10^4 times larger magnetic dipole one, $\Omega_{M_1} = (M_1/\mathrm{Im}E_1^{pv})\Omega_{pv}$. The squared terms are similar in form to the light shifts of allowed transitions, except for their noticeably smaller size. However, the energy shift $\delta E_{F,m_F}$ we are looking for, results from an interference between the dominant Stark-induced amplitude $\Omega_{\mathrm{ind}}^\alpha$, and amplitudes Ω_{pv}, Ω_{M_1},

$$\delta E_{F,m_F} = 2\frac{\hbar\Omega_{\mathrm{ind}}^\alpha(\Omega_{M_1} + \xi\Omega_{\mathrm{pv}})}{\delta_F}\langle F, m_F|\hat{E}\cdot\hat{k}\wedge\vec{\sigma}|F, m_F\rangle, \tag{3}$$

where the detuning δ_F is relative to the $nS_F \to n'S_F$ ($\Delta F = 0$) hf line. It has been convenient to introduce the photon angular momentum $\xi\mathbf{k} = i[\mathbf{e}(\xi)\wedge\mathbf{e}^*(\xi)]\hbar$, the unit vectors $\hat{E}$, $\hat{k}$ along $\mathbf{E}$, $\mathbf{k}$, and $\mathbf{e}(\xi) = (\hat{E} + i\xi\hat{k}\wedge\hat{E})/\sqrt{2}$. Equation (3) expresses that the combined effect of the weak charge interaction and the dressing beam is to create a static PV electric-dipole moment $\propto \xi\hat{k}\wedge\vec{\sigma}$, preserving T-symmetry of magnitude $(\alpha\mathcal{E}^2/\hbar\delta_F)\mathrm{Im}E_1^{pv}$. Because, as justified below, the direction $\hat{B}$ of the weak magnetic field ($B \ll \Delta W/\mu_B$) still defines the quantization axis in the dressed state, we replace the matrix element in Eq. (3) by $g_F m_F$ with $g_F = 2(F-I)/(I+1/2)$. The pseudoscalar $\chi = \hat{E}\wedge\xi\hat{k}\cdot\hat{B}$ is the mark of parity violation affecting the E_1^{pv} contribution. From Eq. (3), we derive the linear Stark frequency shifts $\Delta\nu_{\mathrm{hf}}$ and $\Delta\nu_{\mathrm{Ze}}$, for the $F' = F - 1 \to F$, $\Delta m_F = 0$, hf transitions, and the Zeeman $\Delta|m_F| = 1$ ones,

$$\Delta\nu_{\mathrm{hf}} = \frac{2\Omega_{\mathrm{ind}}^\alpha(\Omega_{M_1} + \xi\Omega_{\mathrm{pv}})}{2\pi\delta_F}(1 + R_F)\frac{m_F\kappa_F}{I + 1/2}\hat{E}\wedge\hat{k}\cdot\hat{B},$$

$$\Delta\nu_{\mathrm{Ze}} = 2\Omega_{\mathrm{ind}}^\alpha\frac{(\Omega_{M_1} + \xi\Omega_{\mathrm{pv}})}{2\pi\delta_F}\kappa_F\hat{E}\wedge\hat{k}\cdot\hat{B}. \tag{4}$$

The quantity $R_F = (\delta_F/\delta_{F'})(\kappa_{F'}/\kappa_F)$ involves the detunings from both $\Delta F = 0$ lines and factors $\kappa_F = 1 + g_F\beta/\alpha$ and $\kappa_{F'}$, close to 1, accounting for $\Omega_{\mathrm{ind}}^\beta$ contributions.

In order to compensate for the weakness of the transition, one obvious solution is to strengthen the radiation field, e.g., by focusing the dressing beam on a small atom sample (0.01 to 1) mm^3 inside a radiative trap. However, two pitfalls have to be avoided: two-photon ionization and radiative instability. The former puts an upper limit on the magnitude of $\mathcal{E}$, while the latter places a constraint on the ratio $\Omega_{\mathrm{ind}}^\alpha/\delta$, such that using large Stark fields brings practically no benefit.

The two-photon ionization rate, computed by quantum defect theory [15], shows peaks close to resonant two-photon transitions. From available spectroscopic data [8] and comparison with Cs, we estimate for Fr at 506 nm $R(s^{-1}) \approx 10^{-49} \times (\text{photon flux})^2$ (nearly the same as for Cs at 539 nm). Supposing from now on a dressing beam intensity of 10 $\mathrm{kW/cm^2}$ (i.e., 2×10^{22} photons $\mathrm{s^{-1}/cm^2}$, $\mathcal{E} = 2.2$ kV/cm), we get conservatively $R = 4 \times 10^{-5}\ \mathrm{s^{-1}}$. For $E \lesssim 10$ kV/cm, $nP - 8S$ admixtures are too small for causing any modification.

On the other hand, the ground state levels acquire a finite lifetime characterized by the decay rate $\Gamma_{nS_F} = \Gamma_{n'S}(\Omega_{\mathrm{ind}}^\alpha/\delta_F)^2$. For precise interferometric measurements, the evolution of the atomic system has to be observed over an interaction time, τ_i, typically 1 s. This means that the dressing intensity has to be kept low enough to satisfy the "stability condition," $\Gamma_{nS_F}\tau_i \leq 1$, over this period. Hereafter, we shall assume this limit is just reached for the most tightly coupled hf state, F. This imposes the size of the ratio $|\Omega_{\mathrm{ind}}^\alpha/\delta_F| = (\Gamma_{n'S}\tau_i)^{-1/2}$, i.e., 2.2×10^{-4} for Cs ($n' = 7$), 2.5×10^{-4} for Fr ($n' = 8$); the sign is that of δ_F (since $\alpha > 0$, and $\mathcal{E}$ and E also by convention). The PV (χ-odd) frequency shift is, then, completely determined:

$$\Delta\nu_{\mathrm{hf}}^{\mathrm{pv}} = (\Gamma_{n'S}\tau_i)^{-1/2}\frac{\Omega^{\mathrm{pv}}}{2\pi}(1 + R_F)\frac{|\delta_F|}{\delta_F}\frac{2m_F\kappa_F}{(I + 1/2)}\chi, \tag{5}$$

with $0 < |R_F| < 1$. The Stark field magnitude E is the single free parameter to determine $\Omega^{\alpha}_{\rm ind}$ once $\mathcal{E}$ is fixed. Since E and $|\delta_F|$ are related by the stability condition, they almost disappear from the result: $\Delta\nu^{\rm pv}$ varies only by a factor 2 from the low field range ($\hbar|\delta|/\Delta W \ll 1$), where the shift of a single hf state dominates, to the high field one ($\hbar|\delta|/\Delta W \gg 1$), where both hf states participate. Given the large E-field magnitudes (>10 kV/cm) such that $\hbar\Omega^{\alpha}_{\rm ind}(\Gamma_{n'S}\tau_i)^{1/2} = \Delta W$, it looks more realistic to envisage the measurement in the low field range, 20 to 1000 V/cm, ($\delta_F/2\pi = 13$ to 650 MHz), much easier to implement. For ^{133}Cs, we obtain $\Omega^{\rm pv}/2\pi = 16.5$ mHz and $\Delta\nu^{\rm pv}_{hf} = 5.2$ μHz for the 3, $\pm3 \rightarrow 4$, ±3 hf transition, while for ^{221}Fr, we expect $\Omega^{\rm pv}/2\pi \simeq 0.30$ Hz leading to $\Delta\nu^{\rm pv}_{\rm hf} \simeq 0.1$ mHz for the 2, $\pm2 \rightarrow 3$, ±2 hf transition; in all cases, $\Delta\nu^{\rm pv}_{\rm Ze} = \Delta\nu^{\rm pv}_{\rm hf}/(I - 1/2)$ (see Table I).

For a precise $E_1^{\rm pv}$ measurement, it is important to suppress the large M_1 contribution to the shift. To this end, one may use forward-backward passages of the dressing beam which changes $\hat{k}$ into $-\hat{k}$ and preserves the photon angular momentum. A possible systematic error arising from the mirror birefringences can be efficiently reduced by making $\pi/2$ rotations of the substrates around their axis [1]. The M_1 contribution, $\propto \mathrm{sgn}(\delta_F m_F)\hat{E}\wedge\hat{k}\cdot\hat{B}$, accessible with a single path of the beam, is a very interesting quantity in its own right. It deserves to be measured precisely because of its exceptional sensitivity to the accuracy of the relativistic description of the atomic system [13]. Here, the δ_F-odd signature would allow discrimination against the M_1-allowed linear Stark shift arising from the far-off-resonant transitions [18].

A crucial step is the calibration procedure allowing for a determination of $E_1^{\rm pv}$ (and M_1) immune from drifts of laser power and atom-sample *vs* beam position. To this end, one can perform simultaneous measurements of the E-field induced PC light shift, namely $\Delta\nu^{\rm ls}_{\rm hf} = |\Omega^{\alpha}_{\rm ind}|^2/2\pi\delta_F$ for $|\delta_F| \ll \Delta W/\hbar$ amounting to ~3 Hz for Cs. In order to discriminate $\Delta\nu^{\rm ls}_{\rm hf}$ against other contributions arising from far-off-resonant allowed transitions (~ -15 Hz), that are nearly independent of ω, one can offset the laser detuning sequentially by a small fractional amount $\pm\eta$ and extract the η-odd contribution. The $\chi_{\rm odd}$, $\eta_{\rm odd}$-ratio $\Delta\nu^{\rm pv}_{\rm hf}/\eta\Delta\nu^{\rm ls}_{\rm hf}$ leads directly the amplitude ratio $\rho^{\rm pv} = E_1^{\rm pv}/\alpha E$, similarly $\rho^M = M_1/\alpha E$, with its own signature, is extracted for a single passage of the beam, $\rho^{\rm pv}/\rho^M$ yields the important parameter $E_1^{\rm pv}/M_1$.

Among all the light- shifts appearing in Eq. (2), we note the absence of crossed term of the type $\Omega^{\alpha}_{\rm ind}\Omega^{\beta}_{\rm ind}$. Indeed, in the present geometry, this term involves the matrix element $\langle F, m_F|\vec{\sigma}\cdot\xi\hat{k}|F, m'_F\rangle$, off-diagonal in the F, m_F basis: it is equivalent to a small transverse magnetic field $B^{\rm ls}$ applied along the laser beam. In a Stark field E of 100 V/cm, $B^{\rm ls} = 2|\frac{\beta}{\alpha}|\Omega^{\alpha 2}_{\rm ind}/(|\delta_F|\mu_B) \simeq 0.4$ μG. However, there are additional contributions associated with the vector Stark shifts coming from the far-detuned allowed transitions, such as $nS_{1/2} - nP_j$ (with $j = 1/2$, $3/2$). This is the dominant source of fictitious magnetic field, amounting to ~6 mG for Cs (30 mG for Fr). Thus, the condition for the applied field remaining the quantization axis during the action of the dressing beam is $B \gtrsim 10$ mG for Cs (50 mG for Fr).

Up to now, we have omitted from the effective dipole operator, Eq. (1), the PV nuclear spin-dependent terms: $\mathbf{D}^{\rm ef}_I = -i\mathrm{Im}E_1^{\rm pv}(\eta\mathbf{I}/I + \eta'\vec{\sigma}\wedge\mathbf{I}/I)$. For small detunings with respect to a $\Delta F = 0$ transition, the second operator $\propto \eta'$ does not participate. From the first one results a shift easily evaluated by direct transposition to $\mathbf{I}\cdot\mathbf{e}(\xi)$ of the reasoning followed for the operator $\vec{\sigma}\cdot\mathbf{e}(\xi)$, leading to Eq. (3). The result involves the matrix element: $\langle F, m_F|\hat{E}\wedge\xi\hat{k}\cdot\vec{I}|F, m_F\rangle = \chi(1 - g_F)m_F$. With $\eta = -2.1\times10^{-2}$ for Cs, this leads to $\sim1\%$ fractional shift corrections of opposite sign for both $\Delta F = 0$ transitions. The Q_W contribution grows with the atomic number much faster than the anapole one [4], so we expect this correction to become a few thousandths for the undeformed ^{210}Fr, $I = 6$ and ^{212}Fr, $I = 5$ isotopes, having small electric quadrupole moments [17]. For a dressing-beam approaching an allowed transition, conversely, the anapole moment contribution [12] is largely dominant.

One can obtain more information by tuning the dressing beam near one of the two $\Delta F = \pm1$ lines, the sole to possess an additional $M_1^{\rm hf}$ amplitude arising from the hf interaction [1]. It can be identified thanks to its contributions of opposite signs on the two lines. Precise theoretical calculations make it an absolute reference with which to calibrate all other amplitudes from the measured ratios [3]. Using such linear Stark shifts to measure $M_1^{\rm hf}/M_1$ in Rb or again in Cs with 0.1% accuracy is highly desirable.

Determination of Q_W from the linear Stark shift in dressed $7S$ Fr atoms involves special requirements: (i) a small (0.01 to 1) mm^3 sample of 10^4 atoms tightly confined in an optical dipole trap, far-blue-detuned and linearly

TABLE I. Atomic parameters of the Cs and Fr forbidden transitions from [2–4,13,16,17], and the PV hf and Zeeman frequency shifts defined in the text, supposing $|\delta_F/2\pi| < 1$ GHz, E(V/cm) $= 1.5\frac{\delta_F}{2\pi}$ (MHz), $\mathcal{E} = 2.2$ kV/cm. For different isotopes, $\Delta\nu^{\rm pv}_{\rm hf}$ varies as $(2I-1)/(2I+1)$ and $\Delta\nu^{\rm pv}_{\rm Ze}$ as $1/(2I+1)$.

Atomic transition	$-\alpha/\beta$	$\lvert E_1^{\rm pv}\rvert/\alpha$ mV/cm	M_1/α V/cm	$\Delta\nu^{\rm pv}_{\rm hf}$ (μHz)	$\Delta\nu^{\rm pv}_{\rm Ze}$ (μHz)
^{133}Cs, $6S - 7S$ (539 nm) $I = 7/2$, $\Delta W = 9.2$ GHz	9.9	0.17	2.99	5.2	1.7
^{221}Fr, $7S - 8S$ (506 nm) $I = 5/2$, $\Delta W = 18.6$ GHz	$\simeq 7$	2.2	$\simeq 10$	100	50

polarized to avoid large frequency shifts; (ii) excitation and detection of a $\Delta m_F = 0$, $(m_F = I - 1/2)$ hf or a Zeeman transition; (iii) application of the dressing circularly-polarized standing-wave of 10 kW/cm^2 with modulated detuning. The crossed fields $E \sim 100$ V/cm, $B \gtrsim 50$ mG are weak, but high stability of B is necessary to prevent its fluctuations δB, from adding noise.

Several groups have produced cold clouds of 10^4 Fr atoms in a MOT [8]. Their rapid (nonadiabatic) transport, with optical tweezers, can be optimized to deliver an ultracold sample on demand to a trap appropriately configured at distance [19]. There is one reported measurement of an alkali hf transition in an optical dipole trap [20], which almost matches the required conditions. It used the Ramsey method, with two time-separated $\pi/2$ pulses of the microwave field. A coherence time of 4 s was observed, but the frequency stability over a few minutes, required here, was not achieved. The effects of drifts at longer term should be reduced by fast reversals of ξ and $\mathbf{E}$, thanks to the clear-cut signature of the PV shift. More recently, progress in optical dipole traps have been reported [21] as well as a project for a three-dimensional optical lattice aiming at another fundamental precision measurement, the Cs electric-dipole moment (EDM) [22]. According to those authors' analysis, this design also appears well adapted to an accurate Ramsey-type measurement of either $\Delta\nu^{\rm pv}_{\rm hf}$ or even $4 \times \Delta\nu^{\rm pv}_{\rm Ze}$. A Raman transition with two $\sigma^{\pm}$ photons can be used to prepare the $F = 2$, $m_F = \pm 2$ atomic coherence to be detected after its evolution in the dressing beam. This also makes it realistic to assume that the projection noise limit [23] lies within reach. The standard deviation of the frequency fluctuations would then be $\delta\nu = 1/(2\pi\tau_i\sqrt{N_{\rm at}})\sqrt{T_c/\tau}$, τ being the total measurement time. If one chooses the duration of a measurement cycle $T_c \approx 2\tau_i$, both $\delta\nu$ and $\Delta\nu^{\rm pv}$ [Eq. (5)] depend on τ_i in an identical manner, and the signal to noise expression $\Delta\nu^{\rm pv}_{hf}/\delta\nu = \Omega^{\rm pv}\sqrt{\tau/2\Gamma_{n'S}}\sqrt{N_{\rm at}}$ becomes independent of τ_i. For an atom number $N_{\rm at} = 10^4$, we find $\delta\nu({\rm mHz}) = 2.2\tau^{-1/2}$. Thus, assuming $\delta B < h\delta\nu/\mu_B = 2$ nG over τ_i, this gives S/N for $\Delta\nu^{\rm pv}_{\rm hf}$ and $4 \times \Delta\nu^{\rm pv}_{\rm Ze}$ equal to 2.5 and 5, respectively, over a 1 h measurement time. For M_1 measurements in Cs, a more conventional Ramsey experiment with a thermal atomic beam deserves consideration, provided all parameters be reoptimized on account of the shorter interaction time.

The main result of this work is that the coupling exerted by the dressing beam between the two lowest n and $n'S$ states transforms the transition parity violating dipole moment, $i{\rm Im}E_1^{\rm pv}\vec{\sigma}$, nuclear-spin independent, into a static electric dipole of the ground state, directed along the vector product of the photon angular momentum and the electron spin. This *static* PV dipole, preserving time-reversal symmetry, gives rise to a linear Stark shift. The price to be paid is the apparition of an instability of the ground state. Since the transition is forbidden, the spontaneous scattering rate can be made acceptable even at small detunings (< 1 GHz) with moderate magnitudes of the E-field assisting the transition. This provides a new method to measure Q_W, involving a very specific left-right asymmetry of the light shift induced by the dressing beam. It avoids two-photon ionization, a problem encountered in previous PV Cs experiments [2] and it can be applied to a sample of only $\sim 10^4$ Fr atoms. Given the continuous production rate $\gtrsim 10^4$ of cold atoms/s now achieved by several groups [8,9], measurement in Fr of the chiral PV Stark shift appears within reach.

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