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Pump-probe measurement of atomic parity violation in caesium with a precision of 2.6%

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We present the atomic parity violation measurements made in Cs vapour using a pump-probe scheme. After pulsed excitation of the 6S-7S forbidden transition in the presence of a longitudinal electric field, a laser beam resonant with one of the 7S-6P transitions stimulates the 7S atom emission for a duration of 20 ns. The polarisation of the amplified probe beam is analysed. A seven-fold signature allows discrimination of the parity violating linear dichroism, and real-time calibration by a similar, known, parity conserving linear dichroism. The zero-field linear dichroism signal due to the magnetic dipole transition moment is observed for the first time, and used for in-situ determination of the electric field. The result, $ImE_1^{pv} = (-808 \pm 21) \times 10^{-14}ea_0$, is in perfect agreement with the corresponding, more precise measurement obtained by the Boulder group. A transverse field configuration with large probe amplification could bring atomic parity violation measurements to the 0.1% accuracy level.

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I. INTRODUCTION

In this paper we present the PV measurements we have performed in Cs [1], by making use of a probe beam superposed with the beam that drives the 6S-7S forbidden transition. After the probe beam has been amplified by stimulated emission of the excited vapour, its polarisation is analysed so as to extract the PV asymmetry, calibrated against a parity conserving signal. This experimental scheme has the potential for high precision PV measurements, since the PV asymmetry to be measured is an increasing function of the excited atom number density. The quantity of metal necessary for vapour cell operation is orders of magnitude smaller than in an atomic beam experiment, and would be acceptable for an experiment with the long lived isotope ^{135}Cs.

II. MOTIVATIONS

Since the emergence of the field [2], atomic parity violation (APV) measurements in heavy atoms have evolved and diversified [3]. These difficult experiments are motivated by the fact that APV measurements provide unique inputs for testing the Standard Model (SM). Measurements at the pole of the Z^0 boson mass energy have reached an impressive precision, but testing, for instance, the variation of the value of the weak mixing angle with energy requires data taken at different energy scales, such as the recent measurement of the PV asymmetry in Møller scattering [4], and the APV measurements in caesium. The corresponding momentum transfers are about 160 MeV/c and a few MeV/c respectively, to be compared with 100 GeV/c at the Z^0 pole. Besides the energy scale, the information extracted from a determination of the Cs weak charge Q_W is a test in the hadronic sector of the SM, and a test different from those extracted, for instance, from the inelastic scattering processes exploited in [5]. In a model-independent analysis of the results, the corresponding allowed regions, in the plane spanned by the elementary weak charges of the u and d quarks, turn out to be nearly orthogonal.

Relevance to physics beyond the SM is one more motivation. APV experiments are particularly sensitive, among the P-violating processes, to those possibly mediated by particles with a mass in the MeV range, while such a "light" boson could escape detection in high energy experiments [6]. The U boson predicted by some supersymmetric extensions of the SM is a candidate to explain, through dark matter recombination, the astrophysical observation that the bulge of the galaxy shows a significant emission at 511 keV [7]. However, to account for the moderate intensity of the emission line, one has to assume [6] that the axial coupling of the U boson (mass ≈ 10 MeV) to electrons is very small. Indeed the present agreement between APV measurements in Cs and the SM [8] excludes such an axial coupling at the 10^{-6} level. Some of the Kaluza-Klein models of space-time also make predictions of effects observable in APV without counterparts in high-energy experiments [9].

The Boulder measurement [10], with two 0.5% precision measurements on two hyperfine (HF) components of the Cs forbidden transition, is the only experiment that could

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achieve a precision test of the standard model at very low energy. Controlling the systematics [11] has been a difficult aspect of this experiment, and a cross-check of this measurement would be highly valuable, in regard of the implications of APV experiments. The experimental scheme developed in Paris and presented in this paper combines the advantages *i)* of the "Stark" (electric field enhanced excitation) experiments: very well defined signature, removing the need for scanning the excitation wavelength to identify the PV signal, and hence the risk associated with the "wavelength-dependent analysis angle" of the optical rotation experiments in heavier atoms; and *ii)* of those latter "transmission" experiments: use of the probe beam allows to detect the whole excited vapour column with high efficiency.

Most importantly, our experimental scheme has only two features in common with those of the Boulder experiment: the choice of the $6S_{1/2}-7S_{1/2}$ forbidden transition and the application of a Stark field, both suggested in [2]. As a result the systematic effects are very different, a crucial point since the measurements presented here aim at a cross-check of the Boulder experiment. Some of the many differences will be highlighted in the text. The most original feature here is the increase of the detected asymmetries with the applied electric field. Our proposal [12] to best take advantage of this feature, will be presented briefly, keeping in mind the goal of APV measurements at the 0.1% level.

III.   PRINCIPLES OF THE EXPERIMENT

A pulsed, 539 nm laser beam excites the $6S_{1/2}, F = 3 \rightarrow 7S_{1/2}, F = 4$ HF transition of Cs while a longitudinal electric field is applied, for a duration of only 100 ns not to trigger discharges in the 8 cm long cell [13]. After this powerful (1.5 mJ in 15 ns) excitation of the forbidden transition, a weak (1 mW), infrared beam stimulates emission on the $7S_{1/2}, F = 4 \rightarrow 6P_{3/2}, F = 4$ allowed transition, for 20 ns. The pump and probe beams are superposed with the same direction $\hat{k}$ and the same linear polarisations $\hat{\epsilon}_{exc} \parallel \hat{\epsilon}_{pr}$. The PV signal is the change of the probe polarisation associated to the excitation of the forbidden transition.

An effective dipole operator [2] can be used to describe the excitation of the forbidden transition:

$$-\hat{\epsilon}_{exc} \cdot \vec{d}_{eff} = \hat{\epsilon}_{exc} \cdot (iImE_1^{pv}\vec{\sigma} - M_1'\vec{\sigma}\wedge\hat{k} + i\beta\vec{\sigma}\wedge\vec{E} + \alpha\vec{E}). \tag{1}$$

The first term is the PV electric dipole amplitude ($\vec{\sigma}$ is the spin Pauli operator, and $iImE_1^{pv}$ is pure imaginary), the second one is the magnetic dipole contribution, and the two last ones are the Stark-induced, respectively vector and scalar, contributions. To give orders of magnitude, the corresponding partial $7S_{1/2}$ lifetimes are about 12 million years for the PV electric dipole amplitude, 12 days for the magnetic dipole amplitude, 300 s and 3 s, respectively, for the vector and scalar Stark-induced transi-

tions in a 2kV/cm $\vec{E}$ field. However, in a longitudinal field $\vec{E}_l = E_l\hat{z}$, the $\alpha\vec{E}\cdot\hat{\epsilon}_{exc}$ term is absent since the excitation polarisation is transverse to $\hat{k} \parallel \hat{z}$. Also important is the fact that, due to the choice of the linearly polarised excitation, the real term $M_1'\vec{\sigma}\wedge\hat{k}$ is out of phase with the $i\beta\vec{\sigma}\wedge\vec{E}_l$ pure imaginary term. This is a crucial difference with the Boulder experiment, where these two terms interfere, which contributes to several systematics [11]. The magnetic term will be omitted throughout, except in sect. VIII where it is exploited for calibration.

In the absence of the P violating term, the effective transition operator (Eq.(1)) would be $\hat{\epsilon}_{exc} \cdot (i\beta\vec{\sigma}\wedge\vec{E}_l) = -i\beta E_l\sigma_x$, assuming that $\hat{\epsilon}_{exc} = \hat{y}$. Adding the PV contribution changes this term into $-i\beta E_l\{\sigma_x - (ImE_1^{pv}/\beta E_l)\sigma_y\}$. Indeed, the PV term has the same, geometrical consequence as a tilt of the excitation polarisation

$$\hat{\epsilon}_{exc} \rightarrow \hat{\epsilon}_{exc} + \theta^{pv}\hat{z}\wedge\hat{\epsilon}_{exc} \tag{2}$$

by an angle $\theta^{pv} = -ImE_1^{pv}/\beta E_l$. As a result, the eigen-axes of the excited state density matrix $\rho_{7S} \propto (\beta E_l\sigma_x)^2 \propto (\beta E_l F_x)^2$ will be tilted as well. Consequently, the vapour will act on the probe as an anisotropic amplifier *with eigen-axes tilted*, by the angle θ^{pv}, *with respect to the symmetry planes* imposed by the direction of the linear polarisation $\hat{\epsilon}_{exc}$. The tilt angle θ^{pv} is small, 10^{-6} radian at $E_l \approx 1.6$ kV/cm, but is odd in E_l reversal, a clear-cut signature. Hence the PV signal will be a change of the linear polarisation of the amplified probe beam, odd under E_l reversal, manifesting the presence, in the probe gain matrix, of a chiral contribution associated with the pseudoscalar $(\hat{\epsilon}_{exc}\cdot\hat{\epsilon}_{pr})(\hat{\epsilon}_{exc}\wedge\hat{\epsilon}_{pr}\cdot\vec{E}_l)$. Although the expected probe polarisation signal can be calculated [14], an efficient calibration has been obtained by deliberately tilting $\hat{\epsilon}_{exc}$ by a known angle θ_{cal} and measuring the corresponding probe polarisation signal in rigorously identical conditions. For θ_{cal} in the milliradian range, proportionality is good enough [15] to allow linear extraction of θ^{pv} from the PV signal. As compared to the Boulder experiment, this calibration procedure is obtained in real-time, and is free from any lineshape correction.

IV.   SHORT REVIEW OF THE SYSTEMATIC EFFECTS

Systematics can be classified as rank-1 or rank-2, according to the number of defects involved.

Rank-1: *i)* A tilt of $\hat{\epsilon}_{exc}$, if it were *odd* in the reversal of the applied electric field, would give rise to a systematic effect: this is looked for and estimated by real time monitoring of $\hat{\epsilon}_{exc}$. *ii)* Remembering that a longitudinal magnetic field induces Larmor rotation of the eigen-axes of the vapour, an E_l-odd B_z field would give rise to a systematic. Although the symmetry of the experiment forbids even an E_l-even B_z field, a significant fraction

of the data acquisition is devoted to the measurement of B_z^-, using atomic signals (see sect. VI).

Rank-2: *i*) An offset between the pump and probe polarisations, in the presence of an *imperfect reversal* of the applied $\vec{E}_l$ field, could give rise to a systematic. However the data processing (see sect. VI) is made in a way that rejects their coupling. In addition, these two imperfections monitored using specific signals are kept below 10^{-4} and 10^{-3}, respectively. *ii*) Defects that break cylindrical symmetry. Ideally, simultaneous rotation of the pump and probe polarisations (and the corresponding polarimeters) should leave the experiment unchanged, except for possible *transverse* electric or magnetic fields, or a misalignment between the excitation and probe beam [16]. The coupling of a transverse electric field to a transverse magnetic field gives rise, in the calibrated probe polarisation signal, to a contribution

$$2\omega_{F'}\tau\frac{E_t}{E_l}(\hat{B}_t \cdot \hat{E}_t - (\hat{B}_t \cdot \hat{\epsilon}_{exc})(\hat{E}_t \cdot \hat{\epsilon}_{exc})), \qquad (3)$$

in which $\omega_{F'}\tau$ is the average Larmor precession under the magnetic field $\vec{B}_t$ during the time spent by the atoms in the excited state. This term mimics the PV E_l-odd term if the $\vec{B}_t$ and $\vec{E}_t$ fields are *both* odd, or *both* even, in $\vec{E}_l$ reversal. When averaged over two polarisations at 90° of each other, this systematic is reduced by a factor of 1/2 ("class 1" systematic effect). On the other hand, the angular dependence, $\hat{B}_t \cdot (\hat{E}_l \wedge \hat{\epsilon}_{exc}) \cdot (\hat{B}_t \cdot \hat{\epsilon}_{exc})$, of the systematic due to the second-order perturbation by a magnetic field completely cancels in the 90° switch polarisation average: "class 2" systematic effect. In ref. [16] can be found the inventory of both class 1 (the most important ones) and class 2 systematic effects.

V. IMPLEMENTATION OF THE EXPERIMENT

We briefly recall the experimental setup, more extensively described in [17], [1], where the absolute frequency stabilisation of the laser sources is presented.

The excitation and probe beams are recombined using a dichroic mirror (see Fig. 1). Beforehand, the polarisation of each of the two beams has been prepared in a "polariser unit" made of a calcite Glan polariser that defines the vertical polarisation, and several half-wave plates that are mechanically inserted to work with horizontal, or +/- 45° polarisation. The excitation polariser unit also includes *i*) a wave plate chosen to be precisely $1 \times \lambda_{exc}$ at *normal incidence*. When appropriately tilted, it allows to compensate the birefringence in the input Cs cell window; *ii*) a Faraday modulator, providing the $\pm\theta_{cal}$ tilts required for the calibration procedure. The probe polariser unit includes a tilted glass plate to compensate for the linear dichroism in the recombination mirror. The "analyser units" are based on a two-channel, balanced-mode polarimeter [18], preceded by several half-wave plates, two of which are inserted synchronously with
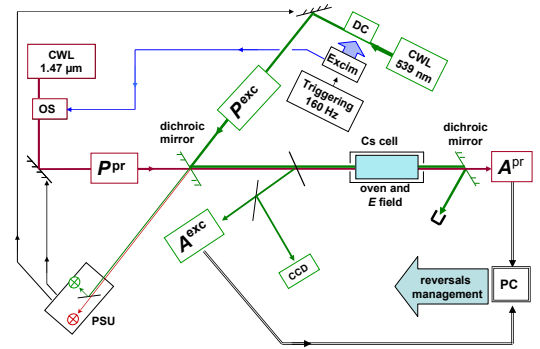

FIG. 1: Main parts of the experimental set-up. CWL: single-frequency, continuous wave laser. OS: sub-nanosecond optical switch. P_{pr}, P_{exc}, A_{pr}, A_{exc}, polariser and analyser units. Excim: excimer laser. DC: dye cells amplifier unit. PSU: beam position stabilisation unit. CCD: camera for excitation beam profile monitoring. PC: computer for data acquisition, and management of the parameter reversals. The two-stage oven allows seperate control of the Cs cell reservoir and wall temperatures.

the half-wave plates of the corresponding polariser unit, so as to operate the polarimeter always in the same conditions. The third half-wave plate has its axes at 45° to the axes of the polarimeter. Inserting this "cleaner" half wave plate allows to reject the polarimeter signals that are not due to a beam polarisation change [19]. The probe analyser records two kinds of signal: the first 20 ns probe shot, immediately after excitation of the forbidden transition, which contains the excited state contribution, and, one ms later, a burst of four probe shots, which serves as a reference for the probe polarisation signals.

Sapphire appeared as an appropriate material for the cell body, due to its very low surface conductivity in the presence of caesium vapour [20]. This should have suppressed the B_z^- field. However, a considerable electron charge (and corresponding current) was observed at the anode window of the sapphire cells, until we could mechanically suppress the multiplication, due to secondary emission, of the electrons emitted at the cathode window [21]. Then the B_z^- field was observed to be at most a few tens of μG, corresponding to a false effect of a fraction of the PV signal (11% on average), for which we can correct practically in real time. Measurement of B_z^- uses the (large) optical rotation signal on the F=4 to F=5 probe transition [22].

VI. MEASUREMENT PROCEDURE

The basic element of the data acquisition is the simultaneous recording of the two signals of the two-channel probe polarimeter, to form the imbalance $D^{ampl} \equiv (S_1 - S_2)/(S_1 + S_2)$ with the *amplified* probe beam. After the reference probe pulses have been detected, the corresponding imbalance is subtracted: $D_{at} \equiv D^{ampl} - D^{ref}$, and this is repeated for 30 shots (duration 200 ms) be-

fore θ_{cal} is reversed. The next reversal is that of the electric field (period 800 ms). Insertion and removal of the "cleaner" half-wave plate is repeated every 7 s. The input probe polarisation undergoes a 90° switch every 14 s. A value θ^{pv} is then obtained by $[\theta^{pv}]_{\hat{\epsilon}_{exc}} = \theta_{cal} \times$

$$\left\langle \sigma_E \left[\frac{< \sigma_{clean} D_{at}(\{\sigma_j\}) >_{\sigma_{clean}\sigma_{cal}}}{< \sigma_{clean}\sigma_{cal} D_{at}(\{\sigma_j\}) >_{\sigma_{clean}\sigma_{cal}}} \right] \right\rangle_{\sigma_E \sigma_{90°pr}} \tag{4}$$

where σ_i indicates the state of reversal (or plate insertion) i. Beside this parity violating, linear dichroism, other linear combinations are monitored for diagnosis of possible drifts or systematics. The probe optical rotation, obtained by inserting a factor $\sigma_{90°pr}$ after the σ_E factor in equation above, is used for measuring the B_z^- field. In order to suppress systematics (see sect. IV), two "isotropic values" of θ^{pv} are obtained, every 5 mn, after $\hat{\epsilon}_{exc}$ has been switched by 90°, then ±45°:

$$S_{xy} \equiv \frac{1}{2}([\theta^{pv}]_x + [\theta^{pv}]_y) \ and \ S_{uv} \equiv \frac{1}{2}([\theta^{pv}]_u + [\theta^{pv}]_v). \tag{5}$$

The recording of isotropic values goes on for about 90 mn, after which a last reversal is performed, concerning the cell orientation with respect to the light beams. Operating at normal incidence at the cell windows gives rise to an excess noise on the polarimetric measurement, due to an etalon, interference effect between the cell windows and optical surfaces inside the polarimeter. To prevent this, the cell is tilted by an angle $\psi = 3 \times 10^{-3}$ rad. However, the atoms excited by the 539 nm beam reflected at the exit cell also contribute. This beam is tilted by an angle 2ψ with respect to the probe beam, and it can be shown that the rank-2 systematic associated with this tilt coupled to a transverse electric field is linear in ψ [16],[1]. It is suppressed by $i)$ reversing the angle ψ, and $ii)$ reducing the window reflection (see sect. VII).

Finally, a PV data-taking run starts and closes with the measurement of the optical rotation on the $4 \rightarrow 5$ probe transition to determine the value of the stray B_z^- field and correct for the associated contribution. This lengthens data acquisition by about 60%. On the other hand, the measurement of the stray, transverse electric and magnetic fields, made by application of large, controlled, transverse magnetic fields, does not increase significantly data taking duration, although it is regularly repeated throughout the data acquisition. In the results presented below, the systematics are controlled and kept at the 1% level. The 2.6% total error bar on the average is mainly statistical, and includes the slight contribution due to the B_z^- systematic correction.

VII. THE PV RESULTS AND THEIR IMPROVEMENT

Seven cells have been used successively for the measurements. The measured values of θ^{pv} are displayed in Fig. 2. For each cell the number N of isotropic values
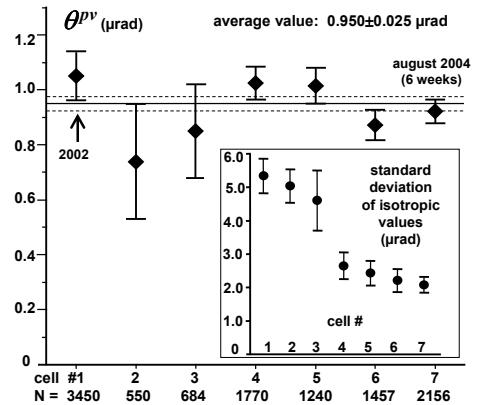

FIG. 2: The values of θ^{pv} measured in the seven successive cells, at electric field 1.62kV/cm. Inset: the standard deviation, as a function of cell number. Adapted from Ref.[1] with permission from APS.

recorded is indicated. The first measurement took place in 2002 [23] and confirmed the validity of the method. Later, efforts devoted to the reduction of the noise and of the systematics have improved the statistics, as is obvious from the inset of Fig.2: the standard deviation of the isotropic values recorded in cell #7 is 2.5 times smaller that in cell #1.

This has resulted from implementing:

- sapphire cells with highly parallel windows [24]. The fraction of the excitation beam reflected at each window can be made very small (10^{-3} instead of 5% in cell #1) by choosing a temperature such that the reflection is cancelled by interference. This further suppresses the systematic effect associated with the tilted reflected beam (see sect. VI). It also suppresses the interference between the beams reflected at the input and exit windows.

- a "polarisation magnifier" [25]. This device, made of 4 or 6 plates at Brewster incidence, enhances the angle of the polarisation tilt to be measured by the polarimeter. Since it attenuates the beam, it allows higher probe power without changing the polarimeter preamplifier chain, improving the signal/noise ratio when the photon shot noise contribution is significant.

- a better extinction for the probe optical switch. The probe intensity that leaks through the closed optical switch can contribute to the noise.

- long term absolute frequency stabilisation of the excitation [1].

A statistical analysis [1] shows that the values obtained in the different cells agree. Indeed the cells were not identical: the material of the cell tube (alumina ceramics vs monocrystalline sapphire), the polishing/origin/tilt of the windows, the filling of the cells (unexpected foreign gas observed in cell #3) etc. were different. The agreement brings confidence in the absence of a bias from cell imperfections. The fact that the averages of the S_{xy} and S_{uv} values agree to about 0.7% also brings confidence as to the cylindrical symmetry of the experiment.

VIII. CALIBRATION ASPECTS; MEASUREMENT OF THE $\vec{E}_l$ FIELD

First, the measurements presented above rely on the determination of the Faraday rotation angle used for calibration of the PV linear dichroism signal. This was done by different methods, in particular by measuring the mechanical rotation of the polariser that compensates for the Faraday rotation, with an accuracy of about 0.5%, that could be improved if need be.

Second, the determination of $\theta^{pv} = -Im E_1^{pv}/\beta E_l$ can be exploited only if E_l is known with enough accuracy *inside the vapour*, i.e., measured by the atoms themselves. This can be done by measuring the Stark parity conserving alignment, proportional to $\theta_{cal}\beta^2 E_l^2$, and then measuring the zero-field alignment, proportional to $M_1'^2$. The proportionality factors are the same, except for the influence of saturation by the probe beam: in the presence of the applied, ≈ 1.6kV/cm electric field, the amplification of the probe beam is non-negligible, while it is very small, and buried in noise and background, in the absence of electric field. An accurate calibration of the electric field can be obtained by the comparison of these two, similar, linear dichroism signals, both measured *vs* probe beam intensity I_{pr} and extrapolated to $I_{pr} = 0$:

$$E_l^{exp} = \frac{M_1'}{\beta}\left(\sqrt{\frac{\ln[1+D_{at}(E=E_l,\theta=\pm\theta_{cal})/2\theta_{cal}]}{(1+\epsilon)D_{at}(E=0,\theta=\pm\pi/4)}} - 1\right)$$

Here the small ϵ quantity expresses the deviation of the exact result, calculated numerically [14], with respect to the simple one assuming an exponential-type amplification. In our experimental conditions [1], we obtain $\epsilon = 0.100$, with a resulting uncertainty of 0.3% on E_l^{exp}. Presently the uncertainty in E_l^{exp} is negligible as compared to the 2.5% uncertainty in the determination of θ^{pv}.

IX. CONCLUSIONS AND PERSPECTIVES

For the measured $E_l^{exp} = 1.619$ kV/cm we obtain $\theta_{exp}^{pv} = (0.950 \pm 0.025)$ μrad, in excellent agreement with the value of 0.962 ± 0.005 obtained from the Boulder measurement [10] on the same 6S, F=3 $\rightarrow$ 7S, F=4 hyperfine transition. Using the value of the β polarisability published in [26], the corresponding value of the P violating transition dipole, $Im E_1^{pv}(3 \rightarrow 4) = -0.808 \times 10^{-11}$ $|e|a_0$, is obtained with a 2.1×10^{-13} $|e|a_0$ absolute uncertainty. Our experimental method is very different from that used by the Boulder group [11], with many consequences as regards calibration, or systematics. It makes use of the amplification of a probe beam, the higher the gain, the larger the asymmetry to be measured. Hence, the PV asymmetry is an *increasing* function of the applied electric field. One important consequence is the considerable enhancement of sensitivity that can be foreseen in an experiment with a *transverse* electric field and a longer interaction length [12]. Despite the transverse field configuration, a special multi-electrode design can "restore cylindrical symmetry", which helps in tracking and rejecting systematic effects [27]. With reasonably moderate values of the probe gain (still far from spontaneous superradiance), a sensitivity of 0.1% looks a realistic objective, although the regime of higher gains (*triggered* superradiance) probably deserves specific attention. The suggested experiment involves the excitation in the presence of transverse magnetic and electric fields, with two counter-propagating excitation beams. It is further motivated by the recent progress in the atomic physics calculations of the factor that links the nuclear spin independant value of E_1^{pv} to the Cs nucleus weak charge, now aiming at the 0.1% accuracy [28].

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