New Manifestation of Atomic Parity Violation in Cesium: A Chiral Optical Gain Induced by Linearly Polarized 6*S*-7*S* Excitation

J. Guéna, D. Chauvat,* Ph. Jacquier, E. Jahier, M. Lintz, S. Sanguinetti,† A. Wasan, and M. A. Bouchiat
Laboratoire Kastler Brossel, 24 Rue Lhomond, F-75231 Paris Cedex 05, France

A.V. Papoyan and D. Sarkisyan
Institute for Physical Researches, Ashtarak-2, 378410, Armenia
(Received 21 October 2002; published 8 April 2003)

We have detected, by using stimulated emission, an atomic parity violation (APV) in the form of a chiral optical gain of a cesium vapor on the $7S$-$6P_{3/2}$ transition, consecutive to linearly polarized $6S$-$7S$ excitation. We demonstrate the validity of this detection method of APV, by presenting a 9% accurate measurement of expected sign and magnitude. We stress several advantages of this new approach which fully exploits the cylindrical symmetry of the setup. Future measurements at the percent level will provide an important cross-check of an existing more precise result obtained by a different method.

DOI: 10.1103/PhysRevLett.90.143001 PACS numbers: 32.80.Ys, 11.30.Er, 33.55.–b

Atomic parity violation (APV) experiments are important as probes of the electron-hadron Z^0 exchange in conditions totally different from those encountered in high energy experiments [1]. The Boulder group [2,3] has made quite an achievement by performing a calibrated [4] measurement of the APV $6S$-$7S$ Cs transition amplitude E_1^{pv}, at a level of precision better than 1%. The importance of this work is illustrated by the abundant literature triggered by the result. An atomic physics calculation is required to arrive at a precise determination of the weak nuclear charge Q_W [1], measuring the interaction strength. Atomic theorists have met the real challenge of reducing their calculation uncertainty below the existing value of 1% [5]. Subtle Breit [6] and radiative [7] corrections, previously omitted, were found to contribute at the few tenths of a percent level. Several authors [3,8] have announced a deviation of 2.5 or 2.2σ between the empirical determination of Q_W and the theoretical value expected in the standard model. Therefore, particle physicists have searched for the possible implications of such a deviation when taken seriously. The best way to account for it, without causing conflict with high energy results, is to admit the existence of an additional neutral vector boson Z_0', whose mass differs according to the models, but always falls around a fraction of TeV [9].

In view of such an important implication, an independent measurement obtained by a totally different method, offering a cross-check of the result, would be extremely valuable. Our experiment has been designed to achieve this. Our approach differs from the Boulder one in two respects: a different emphasis given to the signal-to-noise ratio (SNR) versus the background level and the choice of a new APV physical observable. The idea arose after our first experiment [10] succeeded in illustrating the interest of measurements in the forbidden $6S$-$7S$ Cs transition. It became clear that a novel detection scheme was required to improve their sensitivity. The polarization analysis of the fluorescence light collected only one-thousandth of the photons emitted by the excited $7S$ atoms. We proposed a more efficient scheme based on stimulated emission from $7S$ to $6P_{3/2}$ [11]. As shown in Fig. 1, an intense pulsed laser excites the $6S$-$7S$ transition in a time short compared to the $7S$ lifetime, in a *longitudinal electric field* $\vec{E}_l$, giving rise to a large population inversion and *transient amplification of a probe beam* tuned at resonance for the $7S$-$6P_{3/2}$ transition. Thus, nearly all excited atoms contribute to the signal. The dependence of the amplification on the relative orientation of the linear excitation polarization $\hat{\boldsymbol{\epsilon}}_{\mathrm{ex}}$ and the linear probe one $\hat{\boldsymbol{\epsilon}}_{\mathrm{pr}}$, is the effect which demonstrates APV. *In two mirror-image configurations the excited vapor exhibits different*

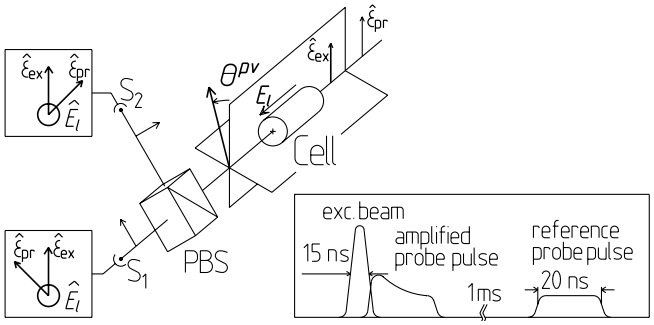

FIG. 1. Schematic of the experiment showing the two orthogonal symmetry planes defined by the electric field $\vec{E}_l$ and the linear excitation polarization $\hat{\boldsymbol{\epsilon}}_{\mathrm{ex}}$. APV gives rise to a tilt θ^{pv} of the optical axes of the excited vapor out of those planes. The incoming probe polarization $\hat{\boldsymbol{\epsilon}}_{\mathrm{pr}}$ provides a superposition of the right- and left-handed $\hat{\boldsymbol{\epsilon}}_{\mathrm{ex}}$, $\hat{\boldsymbol{\epsilon}}_{\mathrm{pr}}$, $\vec{E}_l$ configurations analyzed. The probe amplification difference is directly extracted from the optical signals S_1, S_2, recorded in each channel of the PBS. Inset: timing of the experiment repeated at 100 Hz.

gains, depending on whether the trihedron formed by $\vec{E}_l$, $\hat{\boldsymbol{\epsilon}}_{\rm ex}$, *and* $\hat{\boldsymbol{\epsilon}}_{\rm pr}$ *is either right or left.* In the present Letter, we report on the first APV manifestation via such *a chiral optical gain* which validates our approach.

The pseudoscalar $(\hat{\boldsymbol{\epsilon}}_{\rm ex}\cdot\hat{\boldsymbol{\epsilon}}_{\rm pr})(\hat{\boldsymbol{\epsilon}}_{\rm ex}\wedge\hat{\boldsymbol{\epsilon}}_{\rm pr}\cdot\vec{E}_l)$ appearing in the gain leads to *a tilt* $\theta^{\rm pv}$ *of its optical axes with respect to the symmetry planes* of the experiment (Fig. 1). This tilt is given by the ratio of the PV E_1 amplitude to the vector part of the Stark induced amplitude [1], $\theta^{\rm pv}=-{\rm Im}E_1^{\rm pv}/\beta E_l$, about 1 μrad in current experimental conditions. We note that it is odd under $\vec{E}_l$ reversal. In our experiment, two mirror-image configurations, associated with the beams coming out from the polarizing beam splitter (PBS), are observed simultaneously, as shown in Fig. 1. At the cell input, $\hat{\boldsymbol{\epsilon}}_{\rm pr}$ is aligned along one of the optical axes in the absence of APV, either parallel ($\parallel$) or perpendicular ($\perp$) to $\hat{\boldsymbol{\epsilon}}_{\rm ex}$. During propagation through the vapor, APV induces a small tilt of $\hat{\boldsymbol{\epsilon}}_{\rm pr}$ towards the direction of largest gain. This linear dichroism should not be confused with a true optical rotation. It gives rise to an imbalance, odd under $\vec{E}_l$ reversal, in our two-channel polarization analyzer, operating in the balanced mode in the absence of APV. In an ideal configuration, the imbalance between the optical signals in the two channels, S_1 and S_2, yields a measurement of the left-right (L-R) asymmetry [12]:

$$A_{\rm L\text{-}R}=\frac{(S_1-S_2)}{(S_1+S_2)}=-2\theta^{\rm pv}[\exp(\eta\mathcal{A})-1]. \qquad (1)$$

Here $\mathcal{A}$ is the optical density for the probe and η is the gain anisotropy, equal to $(\alpha_\perp-\alpha_\parallel)/2\alpha_\parallel$, where $\alpha_\parallel$ (respectively, $\alpha_\perp$) is the probe gain per unit length for $\hat{\boldsymbol{\epsilon}}_{\rm ex}\parallel\hat{\boldsymbol{\epsilon}}_{\rm pr}$ (respectively, $\hat{\boldsymbol{\epsilon}}_{\rm ex}\perp\hat{\boldsymbol{\epsilon}}_{\rm pr}$). We selected the $7S_{1/2,F=4}$-$6P_{3/2,F=4}$ hyperfine component leading to the largest value of η, hence the largest L-R asymmetry. As Eq. (1) shows, the greater the optical density, the larger the amplification of both the probe beam and the L-R asymmetry. We took advantage of this by exploiting the high optical densities available in a vapor cell, and by increasing the excitation energy and the $\vec{E}_l$ field magnitude. The exponential growth of the asymmetry with the applied field is the attribute of detection by stimulated emission, contrasting with fluorescence detection where the asymmetry $\propto {\rm Im}E_1^{\rm pv}/\beta E_l$ decreases when E_l is increased. A precise calibration procedure, independent of line shape, optical density, and saturation, has been devised and carefully tested [13]. This consists in deliberately tilting the direction of $\hat{\boldsymbol{\epsilon}}_{\rm ex}$ with respect to $\hat{\boldsymbol{\epsilon}}_{\rm pr}$ by a small precisely calibrated angle $\theta_{\rm cal}$. It can be shown that this causes the probe polarization to rotate by an angle $k\theta_{\rm cal}$, *with the same proportionality factor* k as does the APV angle $\theta^{\rm pv}$. On the other hand, due to the absence of magnetic fields, all atoms belonging to a given hyperfine state contribute and line shape problems coming from overlapping Zeeman components are avoided. In addition, the suppression in the longitudinal E_l-field configuration of the M_1-Stark interference effect, which is a potential source of systematic effect, is welcome. A further attractive feature is the cylindrical symmetry exhibited by the experiment: the signal is expected to remain invariant under simultaneous rotations of the polarizations $\hat{\boldsymbol{\epsilon}}_{\rm ex}$ and $\hat{\boldsymbol{\epsilon}}_{\rm pr}$ about the common beam direction. This feature has enabled us to discriminate against possible systematics arising from stray fields.

Despite the fact that our scheme combines several attractive new features, the observation of the APV chiral optical gain remains an experimental challenge. To make the method work we have had to solve often unexplored experimental problems. Besides a high precision differential polarimeter operating in the pulsed regime [13], our experiment requires both the pulsed excitation laser and the probe laser systems to satisfy uncommon specifications described elsewhere [14]. For instance, it is crucial to restrict the detection to the short time interval ($\sim$20 ns) during which the vapor acts as an amplifier, with the help of a fast optical switch on the probe laser beam. Another major problem was actually to generate a pulsed longitudinal uniform $\vec{E}_l$ field of $\simeq 2$ kV/cm inside a Cs vapor cell at the useful atomic densities ($\simeq 10^{14}/{\rm cm}^3$) and over a length of 80 mm. Moreover, the initial glass cells [14] had to be replaced by alumina ones consisting of an alumina tube, closed by sapphire windows glued at both ends [15]. The surface electrical conductivity of alumina being much lower than that of glass [16], stray magnetic fields induced by electric surface currents are thereby suppressed. With alumina, one can use external electrodes if need be [17]. The sapphire windows, unlike glass ones, retain excellent transparency under intense laser illumination in the presence of the Cs vapor. Finally, one can heat alumina cells to 250–300 °C to thermodissociate troublesome Cs_2 dimers. The $\vec{E}$-field map distortions coming from dimer photoionization by the excitation laser beam [18] are thus strongly reduced. One remaining problem, however, arises from the photoelectrons emitted by the windows. We have shown that these are amplified by secondary electron emission (SEE) from grazing collisions with the walls. An efficient solution has consisted in machining annular grooves with sharp tips in the alumina walls (1 mm apart), making grazing incidence unlikely [19]. This modification of the internal surface reduced the $\vec{E}$, $\vec{B}$ stray fields and enabled us to perform the APV measurements reported here.

The signature of the PV signal first relies on a doubly differential feature of the polarimeter output. The imbalance at each amplified probe pulse, $D^{\rm amp}=\frac{(S_1-S_2)}{(S_1+S_2)}$, is compared to that of four consecutive probe pulses, $D^{\rm ref}$, measured when all $7S$ excited atoms have decayed. Thus the doubly differential signal, $D^{\rm amp}-D^{\rm ref}$, selects at the laser repetition rate ($\sim 100\ {\rm s}^{-1}$) a *true atomic effect,* $D_{\rm at}$, free from the probe polarization rotation arising from polarization defects present on the probe

beam path. Our measurement involves four different physical parameter reversals, listed in order of increasing period: (i) reversal of $\theta_{\rm cal}$, every 0.25 s, providing for real time calibration; (ii) reversal of the $\vec{E}_l$ field every 0.5 s (with 60 ms dead time); (iii) switching of the half-wave plate $(\frac{\lambda}{2})^{\rm det}$ in front of the polarimeter, which performs a symmetry of the outgoing probe polarization with respect to the symmetry plane of the experiment, every 2 s: it allows us to discriminate between true polarization rotations and instrumental imbalances [13]; (iv) switching, with another half-wave plate $(\frac{\lambda}{2})^{\rm pr}$ which acts on the input probe polarization, from para ($\hat{\boldsymbol{\epsilon}}_{\rm ex} \parallel \hat{\boldsymbol{\epsilon}}_{\rm pr}$) to ortho ($\hat{\boldsymbol{\epsilon}}_{\rm ex} \perp \hat{\boldsymbol{\epsilon}}_{\rm pr}$) configuration for discrimination between linear dichroism and optical rotation [13]. Since performing twice a given reversal leaves the system unchanged, for each reversal we introduce one binary variable: $\sigma_{\rm cal}, \sigma_E, \sigma_{\rm det}, \sigma_{\rm pr} = \pm 1$. Thus the complete signature of the APV signal involves an average over all the 2^4 possible states. For a given $f(\sigma)$, we define the average, $\langle f(\sigma)\rangle_\sigma = \frac{1}{2}(f(1) + f(-1))$, i.e., the σ-even part. This implies that $\langle \sigma f(\sigma)\rangle_\sigma = \frac{1}{2}(f(1) - f(-1))$ yields the σ-odd part. The determination of the PV calibrated linear dichroism involves the construction of the following quantity:

$$G = \theta_{\rm cal}\left\langle \sigma_E\left[\frac{\langle \sigma_{\rm det} D_{\rm at}(\{\sigma_j\})\rangle_{\sigma_{\rm det}\sigma_{\rm cal}}}{\langle \sigma_{\rm det}\sigma_{\rm cal} D_{\rm at}(\{\sigma_j\})\rangle_{\sigma_{\rm det}\sigma_{\rm cal}}}\right]\right\rangle_{\sigma_E\sigma_{\rm pr}}. \quad (2)$$

We stress that an imperfect $\vec{E}_l$ reversal leading to a $\vec{E}_{l,\rm odd}$ contribution to $\mathcal{A}$ does not affect this determination.

Moreover, measurements with different orientations of $\hat{\boldsymbol{\epsilon}}_{\rm ex}$ provide important tests for systematic effects associated with stray transverse $\vec{E}_T$ and $\vec{B}_T$ fields (or beam misalignment), since they are related to two preferred directions in the transverse plane. In fact, four orientations suffice because of the structure of the Stark induced dipole. A set of four supplementary $\lambda/2$ plates (two on each beam) enables us to perform successive rotations of $\hat{\boldsymbol{\epsilon}}_{\rm ex}$ (and $\hat{\boldsymbol{\epsilon}}_{\rm pr}$) by steps of 45° (directions $\hat{\imath} = \hat{x}, \hat{u}, \hat{y}, \hat{v}$), while keeping the analyzer fixed [14]. From the four measurements, G_i, we extract two values of the isotropic part, $\frac{1}{2}(G_x + G_y) = \frac{1}{2}(G_u + G_v)$, expected—and actually found—to be equal to within the noise and to average to $\theta^{\rm pv}$. The presence of an anisotropic part manifests itself through the differences $D_{xy} = \frac{1}{2}(G_x - G_y)$ and $D_{uv} = \frac{1}{2}(G_u - G_v)$. The isotropy test consists in plotting one point in the Cartesian coordinate system D_{xy}, D_{uv}, for each cycle of four orientations of $\hat{\boldsymbol{\epsilon}}_{\rm ex}$ and to look for a possible deviation of the center of gravity of the cloud of points associated to all data. Clear anisotropies were sometimes observed. However, since their correlation with the isotropic part is not significant, the latter is negligibly affected. The two isotropic values obtained for each PV cycle (every ~8 mn) were averaged together over a number N of cycles.

Finally, for practical reasons, we are obliged to carry out a further reversal. Although the ideal configuration requires perfect alignment of both laser beams along the cell axis, we have to concede a small tilt angle of the cell axis ($\psi \sim 3$ mrad), in order to avoid an excess of noise in the polarimeter. Since such a tilt breaks the symmetry, we reverse its sign every few hours and we take the average of the results obtained with both tilts, affected in practice by similar statistical noise: $\theta^{\rm pv}_{\rm exp} = \frac{1}{4}\langle \sum_i G_i(\sigma_\psi)\rangle_{N,\sigma_\psi}$.

As a consistency check, we have reconstructed the APV signal in a different way. $D_{\rm at}$ and $\mathcal{A}$ measured for each pulse, yield according to Eq. (1) the tilt of the optical axes, $\theta = -D_{\rm at}/2[\exp(\eta\mathcal{A}) - 1]$. Replacing $D_{\rm at}$ by θ in Eq. (2) provides a second determination of the linear dichroism G. Both methods give identical results.

The validity of the entire acquisition procedure has been tested by programming the reversal of an additional tilt θ_0 of the input polarization $\hat{\boldsymbol{\epsilon}}_{\rm ex}$, *willingly correlated* with $\vec{E}_l$ reversal. It is intended to mimic the APV effect by optical means. More precisely, the tilt and the field are switched in accordance with the following pattern, $(\theta_0 + \theta_{\rm cal}, \vec{E}_l)$, $(\theta_0 - \theta_{\rm cal}, \vec{E}_l)$, $(-\theta_0 + \theta_{\rm cal}, -\vec{E}_l)$, $(-\theta_0 - \theta_{\rm cal}, -\vec{E}_l)$, expected to mimic $\theta^{\rm pv} = \theta_0$. We expect the reconstructed signal G [Eq. (2)] to give $\theta_0 + \theta^{\rm pv}$. This test performed with $\theta_0/\theta_{\rm cal} = 10^{-1}$, has been successful within a precision of 2%. When $\hat{\boldsymbol{\epsilon}}_{\rm ex}$ was rotated by increments of 45°, we tested similarly the isotropy of the polarimetry method, with SNR ~ 100. The θ_0 tilt creates a large linear dichroism γ_1, with no optical rotation α_2. Thus, we also verify the discrimination between γ_1 and α_2, based on the para/ortho reversal. This ensures that the reconstitution method [Eq. (2)] deals correctly with the problem of a large gain anisotropy.

This test also shows the importance of a continuous search for a possible unwanted $\vec{E}_{l,\rm odd}$ tilt of the input excitation polarization during APV measurements. This has been implemented using a visible polarimeter of the same design as the probe polarimeter, with sensitivity about 2.5 times better. Up to now, a stray effect of this kind, which might have arisen from electromagnetic interferences associated with pulsed $\vec{E}_l$ field monitoring, remains buried in noise ($\leq 3.5 \times 10^{-8}$ rad).

There is one more harmful effect which arises from a longitudinal magnetic field reversing with the $\vec{E}_l$ field, $B_z(E_{l,\rm odd})$. This causes a small precession $(E_{l,\rm odd})$ of the parity conserving linear dichroism about the beam axis. In fact, such a B_z field also generates a Faraday optical rotation. The $B_z(E_{l,\rm odd})$ Faraday effect can be isolated and exploited to measure the field magnitude [20]. For this, we select the highly B_z-sensitive $7S_{1/2,F=4}$-$6P_{3/2,F=5}$ line. Owing to the progress which has resulted from grooving the internal surface of the alumina cell [19], the $B_z(E_{l,\rm odd})$ field has remained either practically absent or small (<50 μG) during the measurements reported here and more importantly it has exhibited only very slow drifts. Thus one can correct for its effect, with only a slight increase of the statistical noise, by inserting field measurements between longer periods of APV data averaging.

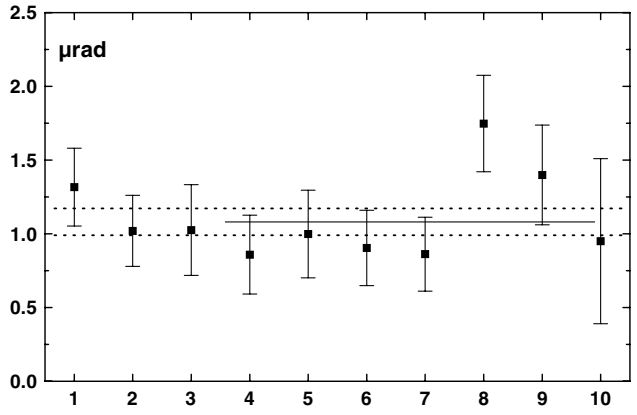

FIG. 2. Experimental values of $\theta^{\rm pv}_{\rm exp}(\mu{\rm rad})$ obtained in successive runs with experimental conditions kept as constant as possible. The solid (respectively, dashed) line represents the mean (respectively, the statistical error on this mean).

We have verified the exactitude of the correction by performing measurements on both transitions, while applying a $B_z(E_{l,\rm odd})$ field of known magnitude.

We have calibrated the magnitude of the E_l field inside the alumina cell by exploiting the atomic signals [21]. Using this calibration leading to $E_l = 1.619$ kV/cm, with 2% accuracy, and the result given in [2], we expect to obtain for the $6S_{1/2,F=3}$-$7S_{1/2,F=4}$ excitation line: $\theta^{\rm pv} = -\frac{{\rm Im}E_1^{\rm pv}}{\beta E_l} = 0.962 \pm 0.020 \times 10^{-6}$ rad.

We have now accumulated 3200 experimental isotropic values of the $E_{l,\rm odd}$ linear dichroism. Figure 2 shows the results of successive runs. The final result is

$$\theta^{\rm pv}_{\rm exp}(\mu{\rm rad}) = 1.082 \pm 0.091({\rm stat}), \qquad (3)$$

which agrees with the expected value within statistical error. The chiral optical gain which manifests APV is thus clearly detected. This validates our method.

The experiment has not yet reached its ultimate sensitivity. The noise is about 2.5 times the shot noise limit. Its sensitivity to optical adjustments proves that extra noise arises from interferences inside the inhomogeneously thick sapphire plates mounted as windows. In our next Cs cell, their parallelism will be much improved. By temperature tuning [22], an excellent reflection minimum $\leq 10^{-3}$ can be achieved and should be accompanied by a strong reduction of the interference noise. For further improvement of the SNR by a factor of $\sim$2, magnification of polarization tilts using a dichroic optical component [23], combined with an optimization of the excitation and probe energies, is going to be implemented. Moreover, we shall benefit from an extra factor of $\sqrt{2}$ by doubling the present repetition rate. In parallel, we are constructing a new type of cell with internal ring electrodes spaced by ceramic braces. This geometry inhibits SEE, while the electrodes connected at fixed potentials tend to evacuate the electrons circulating inside the vapor. Hence, we expect a reduction of the transverse fields [19], still present during the work reported here. All in all combined with an increased acquisition time (now 210 h) by a factor of 3 or 4, these improvements should bring us to within reach of our 1% Q_W-precision objective.

We thank M. D. Plimmer for his participation, L. Pottier for early contributions, and A. Clouqueur for technical assistance. A. W. acknowledges support from CNRS (IN2P3) and S. S. from the European Commission. Laboratoire Kastler Brossel is a Unité de Recherche de l'Ecole Normale Supérieure et de l'Université Pierre et Marie Curie, associée au CNRS (UMR 8552).

*Now at PALMS, Université de Rennes 1, F-35700 Rennes, France.
†Also at Physics Department, Pisa University, Pisa, Italy.

[1] See M. A. Bouchiat and C. Bouchiat, J. Phys. (Paris) **35**, 899 (1974); Rep. Prog. Phys. **60**, 1351 (1997).
[2] C. S. Wood *et al.*, Science **275**, 1759 (1997).
[3] S. C. Bennett and C. E. Wieman, Phys. Rev. Lett. **82**, 2484 (1999).
[4] M. A. Bouchiat and J. Guéna, J. Phys. (Paris) **49**, 2037 (1988); C. Bouchiat and C. A. Piketty, *ibid.* **49**, 1851 (1988).
[5] V. A. Dzuba, V. V. Flambaum, and O. P. Sushkov, Phys. Lett. A **141**, 147 (1989); S. A. Blundell, J. Sapirstein, and W. R. Johnson, Phys. Rev. D **45**, 1602 (1992).
[6] A. Derevianko, Phys. Rev. Lett. **85**, 1618 (2000).
[7] A. I. Milstein and O. P. Sushkov, e-print hep-ph/0109257.
[8] V. A. Dzuba *et al.*, Phys. Rev. D **66**, 076013 (2002).
[9] R. Casalbuoni *et al.*, Phys. Lett. B **460**, 135 (1999); J. Erler and P. Langacker, Phys. Rev. Lett. **84**, 212 (2000); D. E. Groom, http://pdg.lbl.gov/ (Chap. 10).
[10] M. A. Bouchiat, J. Guéna, L. Hunter, and L. Pottier, Phys. Lett. **117B**, 358 (1982); J. Phys. (Paris) **47**, 1709 (1986).
[11] M. A. Bouchiat, Ph. Jacquier, M. Lintz, and L. Pottier, Opt. Commun. **56**, 100 (1985).
[12] D. Chauvat *et al.*, Eur. Phys. J. D **1**, 169 (1998); M. A. Bouchiat and C. Bouchiat, Z. Phys. D **36**, 105 (1996).
[13] J. Guéna *et al.*, J. Opt. Soc. Am. B **14**, 271 (1997); Opt. Commun. **119**, 403 (1995).
[14] J. Guéna *et al.*, Quantum Semiclass. Opt. **10**, 733 (1998).
[15] D. G. Sarkisyan *et al.*, Instrum. Exp. Tech. **32**, 485 (1989).
[16] M. A. Bouchiat *et al.*, Appl. Phys. B **68**, 1109 (1999).
[17] E. Jahier *et al.*, Eur. Phys. J. D **13**, 221 (2001).
[18] M. A. Bouchiat *et al.*, Opt. Commun. **104**, 157 (1993).
[19] J. Guéna *et al.*, Appl. Phys. B **75**, 739 (2002).
[20] M. A. Bouchiat *et al.*, Z. Phys. D **33**, 89 (1995).
[21] This measurement is performed using a circularly polarized excitation beam with the polarimeter operating as a circular analyzer. Then $D_{\rm at} \propto (M_1 + M_1^{\rm hf})^2 + \beta^2 E_l^2$ is detected with E_l on and off. Since $M_1, M_1^{\rm hf}$ and β are precisely known [3], we thus deduce the magnitude of E_l.
[22] E. Jahier *et al.*, Appl. Phys. B **71**, 561 (2000).
[23] D. Chauvat *et al.*, Opt. Commun. **138**, 249 (1997).