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# Vacuum magnetic linear birefringence using pulsed fields : the BMV experiment

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We present the measurement of the vacuum magnetic linear birefringence obtained using the first generation setup of the BMV experiment. Our apparatus is based on an up-to-date resonant optical cavity coupled to a transverse magnetic field. In particular, we detail our data acquisition and analysis procedure which takes into account the symmetry properties of the raw data with respect to the orientation of the magnetic field and the sign of the cavity birefringence. Our current value of vacuum magnetic linear birefringence  $k_{\text{CM}}$  was obtained with about 200 magnetic pulses and a maximum field of 6.5 T. We get  $k_{\text{CM}} = (5.1 \pm 6.2) \times 10^{-21} \text{ T}^{-2}$  at  $3\sigma$  confidence level. This result is also used to extend the excluded region of axion-two photons coupling constant  $g$  as a function of the axion mass  $m_a$ . The best limit is obtained at  $m_a = 3.3 \text{ meV}$  with  $g < 1.9 \times 10^{-6} \text{ GeV}^{-1}$  at  $3\sigma$  confidence level.

## I. INTRODUCTION

It is known since the beginning of the 20<sup>th</sup> century that any medium shows a linear birefringence in the presence of a transverse external magnetic field  $\mathbf{B}$ . This effect is usually known as the Cotton-Mouton (CM) effect (see Ref. [1] and references therein). The existence of such a magnetic linear birefringence has also been predicted in vacuum around 1970 in the framework of Quantum ElectroDynamics (QED) [2, 3]. It is one of the non-linear optical effects described by the Heisenberg-Euler effective lagrangian (see Ref. [4] and references therein) and it can be seen as the result of the interaction of the external magnetic field with quantum vacuum fluctuations. In a vacuum therefore the index of refraction  $n_{\parallel}$  for light polarized parallel to  $\mathbf{B}$  is expected to be different from the index of refraction  $n_{\perp}$  for light polarized perpendicular to  $\mathbf{B}$  such that [4] :

$$\Delta n_{\text{CM}} = n_{\parallel} - n_{\perp}, \quad (1)$$

$$= k_{\text{CM}} B^2. \quad (2)$$

At the first order in the fine structure constant  $\alpha$ ,  $k_{\text{CM}}$  can be written as :

$$k_{\text{CM}} = 2\alpha^2 \hbar^3 / 15\mu_0 m_e^4 c^5, \quad (3)$$

with  $\hbar$  the Planck constant over  $2\pi$ ,  $m_e$  the electron mass,  $c$  the speed of light in vacuum, and  $\mu_0$  the magnetic constant. Using the CODATA recommended values for fundamental constants [5], one obtains :

$$k_{\text{CM}} \sim 4.0 \times 10^{-24} \text{ T}^{-2}. \quad (4)$$

In spite of several experimental attempts, the experimental proof of such a very fundamental QED prediction is still lacking [4]. All recent experiments, both completed or running, measure  $\Delta n_{\text{CM}}$  via the ellipticity  $\psi$  induced

on a linearly polarized light propagating in the birefringent vacuum :

$$\psi = \pi k_{\text{CM}} \frac{L_B}{\lambda} B^2 \sin 2\theta_P, \quad (5)$$

where  $\lambda$  is the light wavelength,  $L_B$  is the path length in the magnetic field, and  $\theta_P = 45^\circ$  is the angle between the light polarization and the birefringence axis. This equation clearly shows that the critical experimental parameter is the product  $B^2 L_B$ . In order to increase the ellipticity to be measured, one usually uses an optical cavity to store light in the magnetic field region as long as possible. The total acquired ellipticity  $\Psi$  is linked to the ellipticity  $\psi$  acquired in the absence of cavity and depends on the cavity finesse  $F$  as :

$$\Psi = \frac{2F}{\pi} \psi. \quad (6)$$

After the theoretical calculations in the 70s, a first measurement of the  $k_{\text{CM}}$  value was published by the BFRT collaboration [6]. It was based on a superconducting magnet providing a maximum field of 3.9 T, and a multipass optical cavity. Spurious signals were always present (see Table V(b) in [6]). Final results gave  $k_{\text{CM}} = (2.2 \pm 0.8) \times 10^{-19} \text{ T}^{-2}$  at  $3\sigma$  confidence level [7] for 34 reflections inside the cavity, and  $k_{\text{CM}} = (3.2 \pm 1.3) \times 10^{-19} \text{ T}^{-2}$  for 578 reflections. In 2008 a new measurement was published by the PVLAS collaboration using a Fabry-Pérot optical cavity and a superconducting magnet providing a 2.3 T field :  $k_{\text{CM}} = (1.4 \pm 2.4) \times 10^{-20} \text{ T}^{-2}$  at  $3\sigma$  [8]. The same experiment at 5 T gave  $k_{\text{CM}} = (2.7 \pm 1.2) \times 10^{-20} \text{ T}^{-2}$  at  $3\sigma$ . More recently a new version of the PVLAS apparatus based on two 2.5 T permanent magnets and a Fabry-Pérot optical cavity reached a noise floor corresponding to  $k_{\text{CM}} = 1.3 \times 10^{-20} \text{ T}^{-2}$  at  $3\sigma$ , but "only when no spurious signal was observed" [9]. All these measurements are summarized in Fig. 1. This clearly shows that vacuum CM measurements are true experimental challenges and that one has to focus not only on getting the best optical sensitivity and maximizing the signal to be measured, but also on minimizing all the

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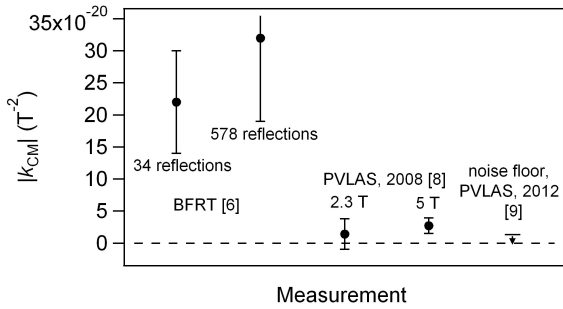


FIGURE 1: Comparison of reported absolute values of the vacuum magnetic linear birefringence and their uncertainties represented at  $3\sigma$ .

unwanted systematic effects by decoupling the apparatus from their sources and by performing an appropriate data analysis.

In this paper we present a measurement of  $k_{CM}$  obtained using the first generation setup of the BMV (*Biréfringence Magnétique du Vide*) experiment at the National High Magnetic Field Laboratory of Toulouse, France (LNCMI-T). The novelty of this experiment is the use of pulsed magnetic fields. This method allows to provide the highest magnetic fields in terrestrial laboratories without destroying the coil itself [4]. Our apparatus is also based on the use of a Fabry-Pérot cavity among the sharpest in the world [10]. We calibrated our experiment using nitrogen gas [10], and published very recently a high precision measurement of the Cotton-Mouton effect of helium gas compatible with the theoretical prediction [11]. We present our data acquisition and analysis procedure that takes into account the symmetry properties of the raw data with respect to the orientation of the magnetic field and the sign of the cavity birefringence. Our current value of  $k_{CM}$  was obtained with 194 magnetic pulses and a maximum field of 6.5 T. This result is compatible at  $3\sigma$  with the expected value for vacuum and corresponds to one of the most precise measurement ever realized. It is therefore a clear validation of our innovative experimental method. Finally, this kind of experiment can also give limits on axion-like particles coupled to two photons travelling through a transverse magnetic field. The value of the vacuum magnetic birefringence is used to extend the excluded region of axion-two photons coupling constant  $g$  as a function of the axion mass  $m_a$ .

## II. EXPERIMENTAL SETUP

### A. Apparatus

Our experimental setup is described in Refs. [10–12]. As shown in Fig. 2, 30 mW of a linearly polarized Nd :YAG laser beam ( $\lambda = 1064$  nm) goes through an acousto-optic modulator (AOM) used in double passage

for an adjustment of the laser frequency. It is then injected into a monomode optical fiber before entering a high finesse Fabry-Pérot cavity of length  $L_c = 2.27$  m, consisting of the mirrors  $M_1$  and  $M_2$ . This corresponds to a cavity free spectral range of  $\Delta^{FSR} = c/2L_c = 65.996$  MHz. The laser passes through an electro-optic modulator (EOM) creating sidebands at 10 MHz. We analyze the beam reflected by the cavity on the photodiode  $Ph_r$ . This signal is used to lock the laser frequency to the cavity resonance frequency using the Pound-Drever-Hall method [13], via the acousto-optic modulator and the piezoelectric and Peltier elements of the laser. All the optical devices from the polarizer to the analyzer are placed in an ultrahigh-vacuum chamber. During operation, the pressure inside the UHV vessel was about  $10^{-7}$  mbar. We have monitored the vacuum quality with a residual gas analyzer.

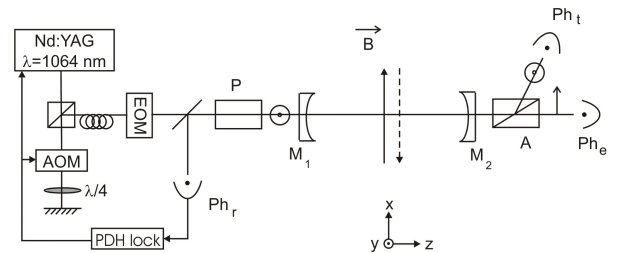


FIGURE 2: Experimental setup. EOM, electro-optic modulator; AOM, acousto-optic modulator; PDH, Pound-Drever-Hall; Ph, photodiode; P, polarizer; A, analyzer. See text for more details.

To measure the ellipticity induced by the Cotton-Mouton effect one needs a transverse magnetic field as high as possible. This is fulfilled using pulsed fields delivered by one magnet, named X-coil, especially designed in our laboratory. The principle of this magnet and its properties are described in details in Refs. [12, 14]. It can provide a maximum field of more than 14 T over an equivalent length  $L_B$  of 0.137 m [10]. Data have been taken with a maximum magnetic field of 6.5 T reached within 1.70 ms while the total duration of a pulse is less than 10 ms as shown in Fig. 3. Moreover, we can remotely switch the high-voltage connections to reverse  $\mathbf{B}$  in order to set it parallel or antiparallel to the  $x$  direction. The maximum repetition rate is 6 pulses per hour.

We infer the cavity finesse from the measurement of the photon lifetime  $\tau$  [10]. Its value is regularly checked during data taking and we get  $\tau = 1.07$  ms. The corresponding finesse is :

$$F = \frac{\pi c \tau}{L_c}, \quad (7)$$

We get  $F = 445\,000$  with a relative variation that does not exceed 6% at the  $3\sigma$  confidence level. This corresponds to a cavity linewidth  $\Delta\nu = c/2FL_c$  of 148 Hz. This is one of the sharpest infrared cavity in the world [10].

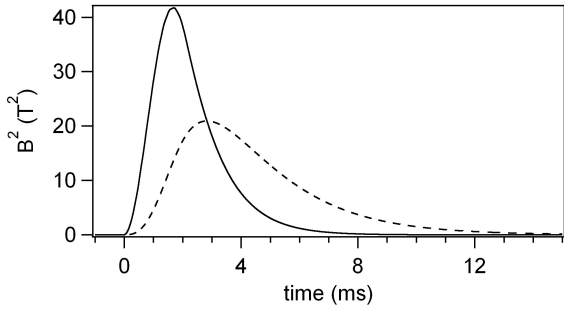


FIGURE 3: Square of the magnetic field amplitude as a function of time for a maximum field of 6.5 T. Solid black curve,  $B^2$ ; dashed curve,  $B_f^2$ .

Before entering the Fabry-Pérot cavity, light is polarized by the polarizer P. The beam transmitted by the cavity is then analyzed by the analyzer A crossed at maximum extinction. We extract both polarizations : parallel and perpendicular to P. The extraordinary ray, whose polarization is perpendicular to the incident polarization, is detected by the photodiode Ph<sub>e</sub> (power  $I_e$ ), while the ordinary ray, whose polarization is parallel to the incident polarization, is detected by Ph<sub>t</sub> (power  $I_t$ ).

### B. Signals

The ellipticity  $\Psi(t)$  induced by the transverse magnetic field is related to the ratio of the extraordinary and ordinary powers as follows :

$$\begin{aligned} \frac{I_e(t)}{I_{t,f}(t)} &= \sigma^2 + [\Gamma + \Psi(t)]^2, \\ &\simeq \sigma^2 + \Gamma^2 + 2\Gamma\Psi(t) \text{ for } \Psi \ll \Gamma, \end{aligned} \quad (8)$$

with  $\sigma^2$  the polarizer extinction ratio and  $\Gamma$  the total static ellipticity. This static ellipticity is due to the mirrors' intrinsic phase retardation [15]. Each mirror can be regarded as a wave plate. The combination of both wave plates gives a single wave plate with a total phase retardation and an axis orientation that depend on each mirror phase retardation and on their relative orientation [16, 17]. Thus, we adjust the value of  $\Gamma$  by rotating the mirrors M<sub>1</sub> and M<sub>2</sub> around the  $z$  axis corresponding to the axis of light propagation.

To measure the polarizer extinction ratio, we first set  $\Gamma = 0$ , with no magnetic field. We get  $I_e/I_{t,f} = \sigma^2 \sim 7 \times 10^{-7}$ . Then, to reach the best sensitivity, we need  $\Gamma^2 \sim \sigma^2$  [12]. Starting from  $\Gamma = 0$  and rotating M<sub>1</sub> in the clockwise or counterclockwise direction, we choose the value of  $\Gamma$  as well as its sign determined by CM measurements in nitrogen and helium gas. The measurement of  $\sigma^2$  and the adjustment of the value and sign of  $\Gamma$  are done before each magnetic pulse.

Due to the photon lifetime, the cavity acts as a first order low pass filter, as explained in details in Ref. [18].

Its complex response function  $H(\nu)$  is given by :

$$H(\nu) = \frac{1}{1 + i\frac{\nu}{\nu_c}}, \quad (9)$$

with  $\nu$  the frequency and  $\nu_c = 1/4\pi\tau \simeq 74$  Hz the cavity cutoff frequency. This filtering has to be taken into account in particular for the time dependent magnetic field applied inside the Fabry-Pérot cavity. The ellipticity  $\Psi$  induced by the external magnetic field is thus proportional to  $B_f^2$  :

$$\Psi(t) = \alpha B_f^2(t), \quad (10)$$

where the filtered field  $B_f^2$  is calculated from  $B^2$  taking into account the cavity filtering. The time profile of  $B_f^2$  is plotted in Fig. 3 with the dashed curve. In particular, we see that the cavity filtering induces an attenuation and a shift of the maximum. The cavity filtering has also to be applied to  $I_t$  as explained in details in Refs. [11, 18].

The calculated signals used for the analysis are described in details in Ref. [11]. In order to extract the ellipticity  $\Psi(t)$  from Eq. (8), we calculate the following  $Y(t)$  signal after each pulse :

$$Y(t) = \frac{\frac{I_e(t)}{I_{t,f}(t)} - I_{dc}}{2|\Gamma|}, \quad (11)$$

$$\simeq \gamma\Psi(t), \quad (12)$$

where  $\gamma$  corresponds to the sign of  $\Gamma$ . The static signal  $I_{dc} = \sigma^2 + \Gamma^2$  is calculated before the pulse as follows :

$$I_{dc} = \left\langle \frac{I_e(t)}{I_{t,f}(t)} \right\rangle_{t_{\Gamma} < t < 0}, \quad (13)$$

where  $t_{\Gamma}$  corresponds to the beginning of the analysis and  $t = 0$  to the beginning of the applied magnetic field. The absolute value of the cavity ellipticity is measured a few milliseconds before each magnetic pulse thanks to the following equation :

$$|\Gamma| = \sqrt{\left\langle \frac{I_e(t)}{I_{t,f}(t)} \right\rangle_{t_{\Gamma} < t < 0} - \sigma^2}. \quad (14)$$

Signals  $Y(t)$  are acquired for both signs of  $\Gamma$  and for both directions of  $\mathbf{B}$  : parallel to  $x$  is denoted as  $> 0$  and antiparallel is denoted as  $< 0$ . This gives four data series : ( $\Gamma > 0, B > 0$ ), ( $\Gamma > 0, B < 0$ ), ( $\Gamma < 0, B < 0$ ) and ( $\Gamma < 0, B > 0$ ). For each series, signals calculated with Eq. (11) are averaged and denoted as  $Y_{>>}$ ,  $Y_{><}$ ,  $Y_{<<}$  and  $Y_{<>}$ . The first subscript corresponds to  $\Gamma > 0$  or  $< 0$  while the second one corresponds to  $\mathbf{B}$  parallel or antiparallel to  $x$ .

## III. DATA ANALYSIS AND RESULTS

### A. Signal duration

The raw signals, such as  $I_t(t)$ ,  $I_e(t)$ ,  $B(t)$  or the cavity locking signal, are recorded 25 ms before the beginning

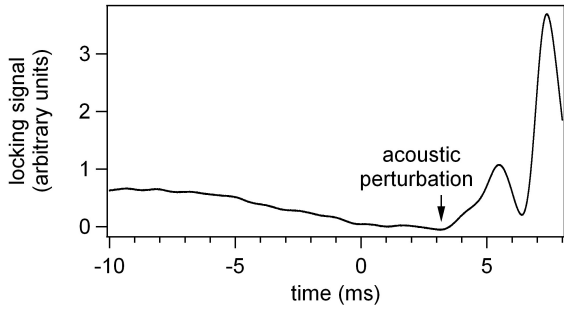


FIGURE 4: Time evolution of the locking signal during a magnetic pulse. The magnetic field is applied at  $t = 0$  ms.

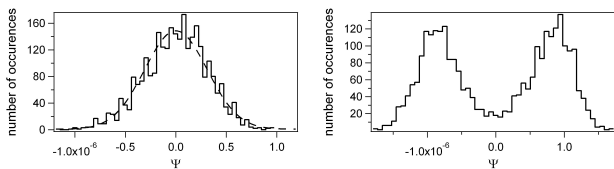
of the magnetic field and 25 ms after. A typical cavity locking signal is plotted in Fig. 4. We clearly see a perturbation which begins at about 3.2 ms. This corresponds to the acoustic perturbation triggered at  $t = 0$  by the magnetic pulse, and that travels through the air to the mirror mounts. We have confirmed the arrival time on the mirror mounts with accelerometers. This perturbation induces an ellipticity noise which degrades our sensitivity. We have thus decided to stop the analysis at  $t = 3.1$  ms. Symmetrically, we start the analysis at  $t_{\Gamma} = -3.1$  ms. It also allows to avoid drifts and long time variations of  $\Gamma$ .

### B. Shot selection

For the measurements reported here, 194 pulses have been applied under vacuum. For each pulse, we first calculate the  $|\Gamma|$  value following Eq. (14). To check that this corresponds to a meaningful value, we plot the histogram of the following signal for  $t_{\Gamma} < t < 0$ :

$$\Psi(t) = \sqrt{\frac{I_e(t)}{I_{t,f}(t)} - \sigma^2} - \Gamma. \quad (15)$$

This corresponds to 3100 values acquired every  $1 \mu\text{s}$ . With white noise and because no induced ellipticity is present at  $t < 0$ , the histogram is centered on 0 and corresponds to a gaussian distribution, as shown in Fig. 5a.



(a) The histogram can be fitted by a gaussian function (dashed curve): the shot is selected.

(b) Rejected shot.

FIGURE 5: Typical histogram of  $\Psi(t)$  before the magnetic pulse.

However, some of the histograms cannot be fitted by a gaussian function, as shown in Fig. 5b. The main origin of this type of distributions is mechanical oscillations of the setup induced by the environment and leading to static ellipticity fluctuations. These mechanical oscillations can be directly observed on the power spectral density (PSD) of the ellipticity  $\Psi$  in the absence of the magnetic field, as shown in Fig. 6. In the case corresponding to Fig. 5b, we cannot give a statistical and significant value of  $\Gamma$ . The corresponding shots are thus rejected. Finally we selected 101 pulses.

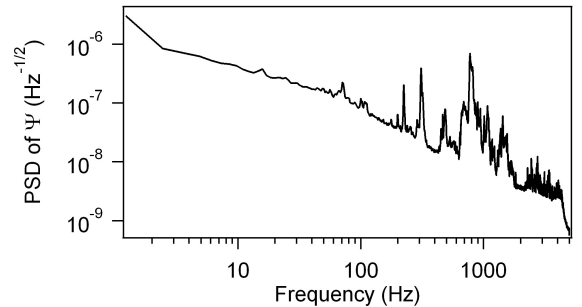


FIGURE 6: Power spectral density of  $\Psi$  in the absence of the magnetic field. We observe the different mechanical resonances of the setup.

### C. Analysis procedure and results

From the 101 selected pulses, we calculate the signals  $Y_{>>}$ ,  $Y_{><}$ ,  $Y_{<<}$ , and  $Y_{<>}$ , denoted  $Y_j$  with  $j = >>, ><, <>, <<$ . As explained in section II B, they correspond to the average of the  $Y(t)$  signals calculated with Eq. (11) for each of the four series. We report them in Fig. 7 with the dark grey curves. The light grey areas correspond to the  $Y_j$  uncertainties calculated at each time  $t_i$ ,  $\Delta Y_j(t_i) = \sigma_j(t_i)/\sqrt{N_j}$ , with  $\sigma_j(t_i)$  the standard deviation of the  $Y_j(t_i)$  distribution and  $N_j$  the number of shots for the  $j$  series.

#### 1. First analysis

If no systematic effects affect the experiment, we can fit the  $Y_j(t)$  averaged signals by  $\gamma \alpha B_f^2(t)$  following Eqs. (10) and (12). The fits are superimposed on the experimental data in Fig. 7. We obtain, for example,  $\alpha = (2.69 \pm 0.09) \times 10^{-8} \text{T}^{-2}$  at  $3\sigma$  confidence level for  $Y_{>>}$ . The Cotton-Mouton constant  $k_{\text{CM}}$  is finally deduced from the measured experimental parameters as follows [10]:

$$k_{\text{CM}} = \frac{\alpha}{4\pi\tau\Delta^{\text{FSR}}} \frac{\lambda}{L_B} \frac{1}{\sin 2\theta_P}. \quad (16)$$

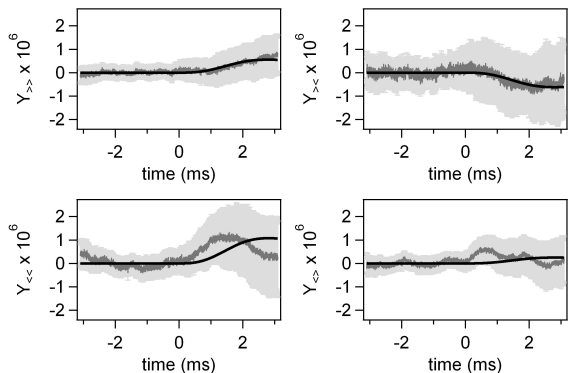


FIGURE 7: Time dependence of the  $Y_j$  signals (dark grey curve). Uncertainties at  $3\sigma$  are plotted in light grey. The fit  $\alpha B_F^2(t)$  is superimposed in black.

From  $Y_{>>}$ , we get  $k_{\text{CM}} = (2.4 \pm 0.2) \times 10^{-19} \text{ T}^{-2}$  at  $3\sigma$  confidence level. The uncertainty takes into account the A-type and B-type uncertainties. The A-type uncertainties come from the fit and from the photon lifetime with a relative variation lower than 6% at  $3\sigma$ . The B-type uncertainties have been evaluated previously and detailed in Ref. [10]. They essentially come from the length of the magnetic field  $L_B$  with a relative uncertainty of 6.6% at  $3\sigma$ .

This result is not compatible with the QED prediction. It can have several origins : residual gases or cavity mirrors. Concerning residual gases, most important contributions come from  $\text{N}_2$  and  $\text{O}_2$  leading to a  $k_{\text{CM}}$  of  $1.5 \times 10^{-23} \text{ T}^{-2}$ . An estimation of the CM effect of high-finesse dielectric mirrors has been reported in Ref. [19] with an induced ellipticity of  $8 \times 10^{-10} \text{ rad.T}^{-2}$  per reflection. The transverse magnetic field at the mirror position is smaller than  $150 \mu\text{T}$ , corresponding to  $k_{\text{CM}} < 1 \times 10^{-24} \text{ T}^{-2}$ . All these CM effects are smaller than the one measured.

Furthermore, none of the four results are compatible with each other. In particular, we expect the sign of the  $Y_j$  variation to change with the sign of  $\Gamma$ , as defined in Eq. (12). As  $Y_{>>}$  increases when the magnetic field is applied,  $Y_{><}$  should increase, whereas  $Y_{<<}$  and  $Y_{<>}$  should decrease. As shown in Fig. 7, this is clearly not the case. Finally, the fit does not match with the experimental signal for  $Y_{<<}$  and  $Y_{<>}$ . This phenomenon was also observed for the measurements of the Cotton-Mouton effect in helium gas [11] where a more general analysis has been developed.

## 2. Second analysis

Actually, as explained in details in Ref. [11], one has to consider systematic effects that mimic the CM effect we want to measure. We thus derive a more general expression taking into account the symmetry properties of  $Y_j$

towards experimental parameters :

$$\begin{aligned}
 Y_{>>} &= a_{>>} S_{++} + b_{>>} S_{+-} + c_{>>} S_{--} + d_{>>} S_{-+}, \\
 &= a_{>>} S_{++} + b_{>>} S_{+-} + c_{>>} S_{--} + \Psi, \\
 Y_{><} &= a_{><} S_{++} - b_{><} S_{+-} - c_{><} S_{--} + d_{><} S_{-+}, \\
 &= a_{><} S_{++} - b_{><} S_{+-} - c_{><} S_{--} + \Psi, \\
 Y_{<<} &= a_{<<} S_{++} - b_{<<} S_{+-} + c_{<<} S_{--} - d_{<<} S_{-+}, \\
 &= a_{<<} S_{++} - b_{<<} S_{+-} + c_{<<} S_{--} - \Psi, \\
 Y_{<>} &= a_{<>} S_{++} + b_{<>} S_{+-} - c_{<>} S_{--} - d_{<>} S_{-+}, \\
 &= a_{<>} S_{++} + b_{<>} S_{+-} - c_{<>} S_{--} - \Psi.
 \end{aligned}$$

The  $S$  functions correspond to a given symmetry towards the sign of  $\Gamma$  and the direction of  $\mathbf{B}$ . The first subscript + (resp. -) indicates an even (resp. odd) parity with respect to the sign of  $\Gamma$ . The same convention is used for the second subscript corresponding to  $\mathbf{B}$ . Each  $S$  function has a different physical origin which are summarized in Tab. I. CM effect signal contributes to  $S_{-+}$  since it depends on the cavity birefringence  $\Gamma$  and on the square of the magnetic field amplitude as shown in Eqs. (5) and (12). We can thus replace  $dS_{-+}$  by  $\gamma\Psi$ .

$S$ signal	Physical effect
$S_{++}(t)$	$\Theta_F^2(t), \Psi^2(t)$
$S_{+-}(t)$	$\mathbf{B}$ effects on photodiodes
$S_{--}(t)$	$\gamma\Theta_F(t)$
$S_{-+}(t)$	$\gamma\Psi(t)$

TABLE I: Possible physical effects contributing to the  $S$  signals. The  $\Theta_F$  signal corresponds to a polarization rotation angle due to the circular birefringence induced by a longitudinal magnetic field (Faraday effect).

The  $S$  functions can be extracted with a linear combination of  $Y_j$  as follows :

$$\begin{aligned}
 J_1 &\equiv \frac{Y_{>>} + Y_{><} + Y_{<<} + Y_{<>}}{4}, \\
 &= \bar{a} S_{++} + \Delta b_1 S_{+-} + \Delta c_1 S_{--} + \Delta d_1 S_{-+}, \\
 J_2 &\equiv \frac{Y_{>>} - Y_{><} - Y_{<<} + Y_{<>}}{4}, \\
 &= \Delta a_2 S_{++} + \bar{b} S_{+-} + \Delta c_2 S_{--} + \Delta d_2 S_{-+}, \\
 J_3 &\equiv \frac{Y_{>>} - Y_{><} + Y_{<<} - Y_{<>}}{4}, \\
 &= \Delta a_3 S_{++} + \Delta b_3 S_{+-} + \bar{c} S_{--} + \Delta d_3 S_{-+}, \\
 J_4 &\equiv \frac{Y_{>>} + Y_{><} - Y_{<<} - Y_{<>}}{4}, \\
 &= \Delta a_4 S_{++} + \Delta b_4 S_{+-} + \Delta c_4 S_{--} + \bar{d} S_{-+}.
 \end{aligned} \tag{17}$$

$J_1(t)$ ,  $J_2(t)$ ,  $J_3(t)$  and  $J_4(t)$  are plotted in Fig. 8. Their uncertainties are calculated from the  $Y_j$  uncertainties. The weighting parameters  $a$ ,  $b$ ,  $c$  and  $d$  depend on the experimental adjustment from pulse to pulse and from day to day. Their relative variations are small :  $\Delta a/\bar{a}, \Delta b/\bar{b}, \Delta c/\bar{c}, \Delta d/\bar{d} \ll 1$ .  $\Delta a$ ,  $\Delta b$  and  $\Delta c$  are mainly

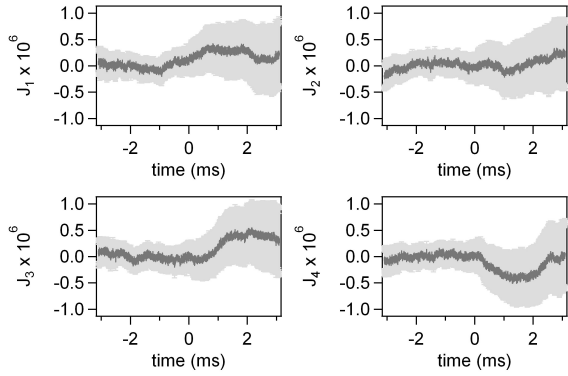


FIGURE 8: Time evolution of  $J_1$ ,  $J_2$ ,  $J_3$  and  $J_4$  (dark grey curve) and their uncertainties at  $3\sigma$  confidence level (light grey).

due to the  $\Gamma$  variation from one shot to another and we can precisely calculate them since  $\Gamma$  is measured for each shot. We obtain  $\Delta a_4/\bar{a} = 5.97 \times 10^{-2}$ ,  $\Delta b_4/\bar{b} = -7.67 \times 10^{-2}$  and  $\Delta c_4/\bar{c} = -8.27 \times 10^{-2}$ . These values are of the same order of magnitude as the one obtained during the CM measurement of helium gaz [11].  $\Delta d$  is independent of the  $\Gamma$  variation. It mainly comes from a variation of the magnetic field from one pulse to another. As the  $B$  relative variation is small compared to the  $\Gamma$  relative variation we consider  $\Delta d \simeq 0$ . The variation of  $\Psi$  is thus neglected.

We thus write :

$$\begin{aligned} J_1 &\simeq \bar{a} S_{++}, \\ J_2 &\simeq \bar{b} S_{+-}, \\ J_3 &\simeq \bar{c} S_{--}, \\ J_4 &\simeq \frac{\Delta a_4}{\bar{a}} J_1 + \frac{\Delta b_4}{\bar{b}} J_2 + \frac{\Delta c_4}{\bar{c}} J_3 + \Psi. \end{aligned} \quad (18)$$

We then calculate :

$$\begin{aligned} J'_4 &\equiv J_4 - \left[ \frac{\Delta a_4}{\bar{a}} J_1 + \frac{\Delta b_4}{\bar{b}} J_2 + \frac{\Delta c_4}{\bar{c}} J_3 \right], \\ &\simeq \Psi, \end{aligned} \quad (19)$$

which corresponds to the Cotton-Mouton signal. It is plotted in Fig. 9.

We fit  $J'_4$  by  $\alpha B_f^2$ . We obtain  $\alpha = (-1.46 \pm 0.07) \times 10^{-8} \text{ T}^{-2}$  at  $3\sigma$  confidence level corresponding to  $k_{\text{CM}} = (-1.3 \pm 0.1) \times 10^{-19} \text{ T}^{-2}$ .

### 3. Third analysis

Nevertheless, as we see in Fig. 9, the fit does not match with the experimental data. This is confirmed by a high associated value of  $\chi^2$  for this fit. Thus, the major component of  $J'_4$  is not  $\alpha B_f^2$  but a supplementary systematic effect.

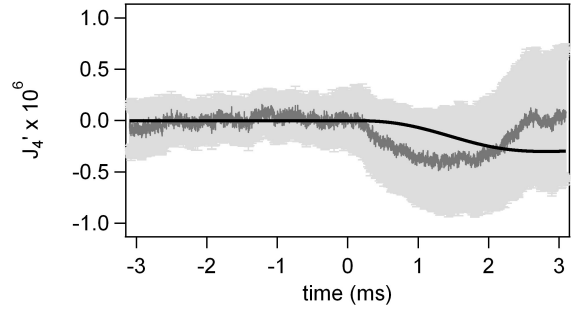


FIGURE 9: Dark grey curve : time evolution of  $J'_4$  and its  $3\sigma$  uncertainties (light grey). Black curve : fit with  $\alpha B_f^2$ .

As discussed in Sec. III B, the setup is subject to several mechanical resonances which can be excited both by the environment and the magnetic field. The latter could thus trigger a mechanical oscillation of the setup at  $t = 0$ . We try to fit  $J'_4$  by a sine function starting at  $t = 0$ . The fit gives a frequency of  $(180 \pm 3) \text{ Hz}$  and it is superimposed to  $J'_4$  in Fig. 10. We finally fit the residues by  $\alpha B_f^2$  and we obtain :

$$k_{\text{CM}}^{\text{noise floor}} = (-0.9 \pm 6.2) \times 10^{-21} \text{ T}^{-2}, \quad (20)$$

at  $3\sigma$  confidence level. This corresponds to our noise floor, which is half the one of the PVLAS collaboration in 2012 obtained with an integration time of 8192 s [9].

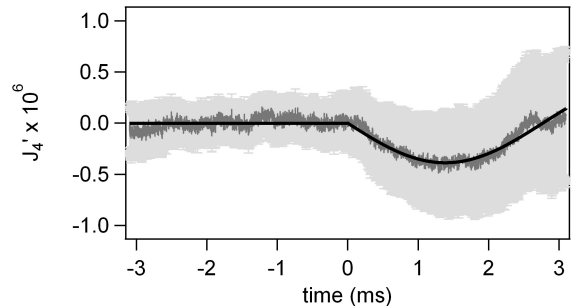


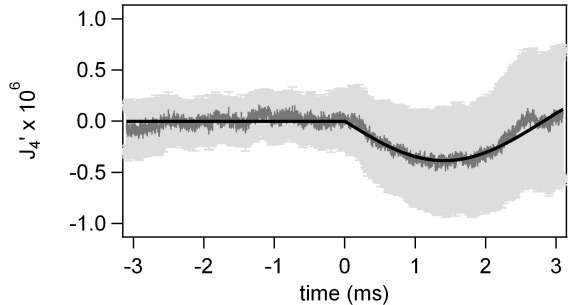
FIGURE 10: Time evolution of  $J'_4$  and its residues (dark grey). The  $3\sigma$  uncertainties are superimposed in light grey. Black curve : fit with a sine function at 180 Hz.

In order to assess more precisely the physical origin of the systematic effect, we zoom in the power spectral density of  $\Psi$ , depicted in Fig. 6, on the frequencies around 180 Hz. We find several resonances at 177 Hz, 200 Hz and above. The signal  $J'_4$  is then fitted by a sine functions but with the frequency fixed to each of the resonance frequencies. The best fit, corresponding to the best  $\chi^2$ , is obtained for 177 Hz, which is compatible with the frequency given by the previous fit. This fit is shown in Fig. 11a, superimposed to the experimental data. Fitting the residues by  $\alpha B_f^2$  gives our final value for the CM

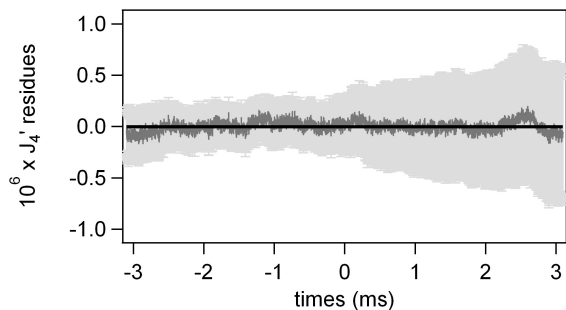
constant :

$$k_{\text{CM}} = (5.1 \pm 6.2) \times 10^{-21} \text{ T}^{-2}, \quad (21)$$

at  $3\sigma$  confidence level. The fit is superimposed to the residues of  $J_4'$  in Fig. 11b.



(a) Time evolution of  $J_4'$ . Black curve : fit with a sine function at 177 Hz.



(b) Time evolution of the residues of  $J_4'$ . Black curve : fit with  $\alpha B_f^2$ .

FIGURE 11: Time evolution of  $J_4'$  and its residues (dark grey). The  $3\sigma$  uncertainties are superimposed in light grey.

Our  $k_{\text{CM}}$  value is compatible with the expected one for the vacuum. We compare it to the other published values in Fig. 12. We see that our value is the most precise value ever realized.

#### IV. AXIONS

The study of photon propagation in transverse magnetic fields is also a powerful test of physics beyond the standard model. In particular, it has been predicted that photons in a magnetic field could oscillate via Primakoff effect into weakly interacting massive particles (WIMPs) like the axion. This hypothetical particle was introduced by Peccei and Quinn to solve the “strong CP problem” [20] and it could be a possible constituent of dark matter.

Most stringent limits on axion or axion-like particles parameters, essentially its mass  $m_a$  and the coupling constant  $g$  of axion-like particle to two photons, are given

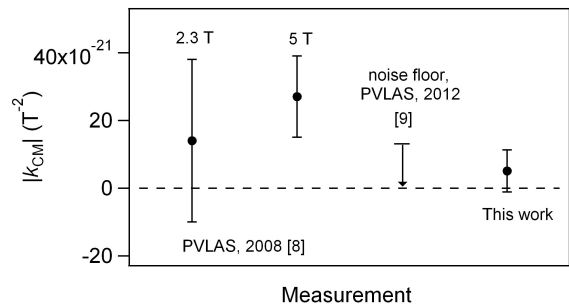


FIGURE 12: Comparison of the latest absolute reported values of the vacuum CM effect. Error bars are given at  $3\sigma$ .

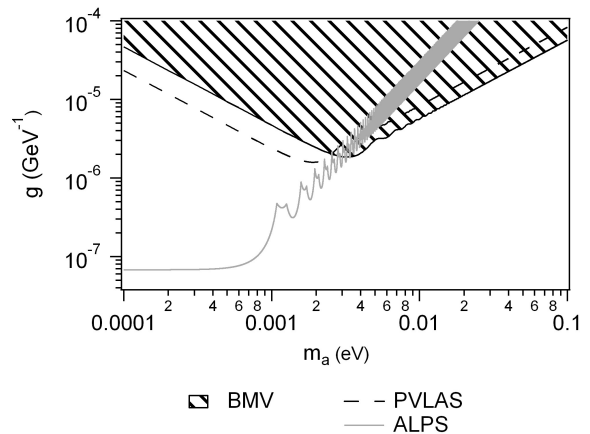


FIGURE 13: Limits at  $3\sigma$  confidence level on the axion-like particle-two photons coupling constant  $g$  as a function of the particle mass  $m_a$  obtained by purely terrestrial experiments. Excluded regions are above the line. Solid black line and striped area : our limit ; dashed line : limit given by the PVLAS collaboration [9] ; grey line : limit given by the ALPS collaboration [24].

by astrophysical observations [21, 22]. But these limits depend on assumptions for the celestial sources. On the other hand, purely terrestrial experiments, where axions are produced and then detected on earth, are less sensitive but much more reliable since the experimental limits do not depend on any physical model.

Three kinds of purely terrestrial experiments exist. The first one corresponds to the “light shining through the wall” experiment [23]. Up to now, the best limits have been obtained at DESY by the ALPS collaboration [24], depicted as the grey line in Fig. 13. The area above the curve corresponds to the excluded region. The second kind of experiments consists in measuring the vacuum magnetic dichroism, i.e. the light absorption in vacuum depending on the light polarisation due to the presence of a transverse magnetic field. The most advanced experiment is performed by the PVLAS collaboration [8, 9].

The third kind of experiment, complementary to the



first ones, consists in measuring the vacuum magnetic birefringence, as described in this paper. Indeed, photon oscillations into a virtual massive particle like axions also induce an ellipticity signal in such an apparatus [25]. This ellipticity can be written as [6] :

$$\Psi = \frac{2F}{\pi} \frac{\Delta_g^2}{2\Delta_{\text{osc}}} L_B \left( 1 - \frac{\sin[\Delta_{\text{osc}} L_B]}{\Delta_{\text{osc}} L_B} \right), \quad (22)$$

with  $\Delta_g = gB/2$ ,  $\Delta_{\text{osc}} = m_a^2/2\omega$  and  $\omega$  the photon energy. Our current limit obtained in vacuum and given in Eq.(21) corresponds to an ellipticity limit of  $\Psi < 1.5 \times 10^{-8}$  rad at  $3\sigma$  confidence level. The black line and striped area in Fig. 13 corresponds to our current limit. The main advantage of this experiment is to extend limits for the heavier axion masses. The best limit is obtained at  $m_a = 3.3$  meV with  $g < 1.9 \times 10^{-6}$  GeV $^{-1}$  at  $3\sigma$  confidence level.

## V. CONCLUSIONS AND PERSPECTIVES

We presented the last advances of our BMV apparatus in terms of axion search, and the most precise measurement of vacuum magnetic birefringence ever realized. Our result validates our experimental method based on pulsed fields. In particular, it proves that the sensitivity obtained in a single pulse compensates the loss of duty cycle. To reach the QED value, the needed improvement is of three orders of magnitude. This is not conceivable with this first-generation experiment. Our strategy is therefore to increase the magnetic field thanks to the pulsed

technology. At the moment, we have  $B^2 L_B = 5.8$  T $^2$ m but we conceptualized and tested a pulsed coil prototype that has already reached a  $B^2 L_B$  higher than 300 T $^2$ m. Two coils of this type will be inserted in the experiment in the near future. This essential milestone really makes the vacuum birefringence measurement within our reach.

On the other hand, our analysis has allowed us to identify some systematic effects. Obviously, a special care will be devoted to limit them in order to improve the accuracy. The magnetic field induces an excitation on the setup which resonates at different frequencies. Since it affects the signal  $J_4$ , the resonance at 177 Hz has an odd symmetry with respect to the sign of  $\Gamma$ . This implies that it concerns the mirror mounts. In order to get rid of this effect, a new setup was designed, providing a better magnetic insulation of the mirrors. It will also provide a better acoustic insulation of the mirror mounts, improving the overall sensitivity and decreasing the number of rejected shots.

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