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The PVLAS experiment for measuring the magnetic birefringence of vacuum

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Summary. — We describe the principle and status of the PVLAS experiment being prepared at the Department of Physics and INFN section in Ferrara, Italy. The goal of the experiment is to measure the magnetic birefringence of vacuum. This effect is directly connected to the vacuum QED structure and can be detected by measuring the ellipticity acquired by a linearly polarized laser beam traversing a strong magnetic field. Vacuum magnetic birefringence is predicted by the Euler-Heisenberg effective Lagrangian. The experimental method is also sensitive to new physics and could place new laboratory limits to hypothetical particles coupling to two photons, such as axion like particles, or millicharged particles.

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1. – Introduction

It is well known that Maxwell's equations in vacuum are linear: the superposition principle is valid for electromagnetic fields. Heisenberg's principle, though, allows vacuum to fluctuate producing virtual pairs of particles which, if charged, lead to non-linear effects in vacuum such as light-light scattering through the box diagram where four photons can interact. For energies well below the electron mass and fields well below their critical values $B \ll B_{\rm crit} = m_e^2c^2/e\hbar = 4.4 \cdot 10^9$ T, $E \ll E_{\rm crit} = m_e^2c^3/e\hbar = 1.3 \cdot 10^{18}$ V/m, such non-linear electrodynamic effects, can be described by the Euler-Heisenberg effective

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Lagrangian correction first derived in 1936 [1] (in S.I. units)

$$(1)\quad \mathcal{L}_{\mathrm{EH}}=\frac{A_e}{\mu_0}\left[\left(\frac{E^2}{c^2}-B^2\right)^2+7\left(\frac{\vec{E}}{c}\cdot\vec{B}\right)^2\right] \quad \text{with} \quad A_e=\frac{2}{45\mu_0}\frac{\alpha^2\lambda\!\!\!^{-}_e{}^3}{m_e c^2}=1.32\cdot 10^{-24}\,\mathrm{T}^{-2},$$

where μ_0 is the magnetic permeability of vacuum, $\lambda\!\!\!^{-}_e$ being the Compton wavelength of the electron, $\alpha = e^2/(\hbar c 4\pi\epsilon_0)$ the fine structure constant, m_e the electron mass, c the speed of light in vacuum.

As shown by Adler [2] the magnetic birefringence of vacuum can be calculated by determining the electric displacement vector $\vec{D}$ and magnetic intensity vector $\vec{H}$ from the total Lagrangian density $\mathcal{L} = \mathcal{L}_{\mathrm{Cl}} + \mathcal{L}_{\mathrm{EH}}$ by using the constitutive relations

$$(2)\qquad \vec{D}=\frac{\partial\mathcal{L}}{\partial\vec{E}} \qquad \text{and} \qquad \vec{H}=-\frac{\partial\mathcal{L}}{\partial\vec{B}}\,.$$

Light propagation in an external field can now be described using Maxwell's equations in media. By assuming a linearly polarized beam of light propagating perpendicularly to an external magnetic field $\vec{B}_{\mathrm{ext}}$ there are two possible configurations: light polarization parallel to $\vec{B}_{\mathrm{ext}}$ and light polarization perpendicular to $\vec{B}_{\mathrm{ext}}$. If we denote the electric and magnetic fields of the laser beam with the subscript γ, and we substitute $\vec{E} = \vec{E}_\gamma$ and $\vec{B} = \vec{B}_\gamma + \vec{B}_{\mathrm{ext}}$ in the expressions obtained from (2) one finds the following relations for the relative dielectric constants, magnetic permeabilities and index of refraction:

$$(3)\qquad \begin{cases} \epsilon_\parallel = 1 + 10A_e B^2_{\mathrm{ext}}, \\ \mu_\parallel = 1 + 4A_e B^2_{\mathrm{ext}}, \\ n_\parallel = 1 + 7A_e B^2_{\mathrm{ext}}, \end{cases} \qquad \begin{cases} \epsilon_\perp = 1 - 4A_e B^2_{\mathrm{ext}}, \\ \mu_\perp = 1 + 12A_e B^2_{\mathrm{ext}}, \\ n_\perp = 1 + 4A_e B^2_{\mathrm{ext}}. \end{cases}$$

From these sets of equations two important consequences arise: the velocity of light in the presence of an external magnetic field is no longer c and vacuum is birefringent:

$$(4)\qquad \Delta n = 3A_e B^2_{\mathrm{ext}}.$$

With $B_{\mathrm{Ext}} = 2.5\,\mathrm{T}$ numerically this leads to a birefringence of

$$(5)\qquad \Delta n = 3A_e B^2_{\mathrm{ext}} = 2.5\cdot 10^{-23}.$$

Furthermore, hypothetical neutral particles coupling to two photons may also allow the interaction between two photons. These effects also result in $v \neq c$, birefringence, and dichroism in the presence of an external field (magnetic or electric). The Lagrangian densities describing the interaction of either pseudoscalar fields ϕ_{a} or scalar fields ϕ_{s} with two photons can be expressed as (written in natural Heavyside-Lorentz units)

$$(6)\qquad \mathcal{L}_a = \frac{1}{M_a}\phi_a \vec{E}\cdot\vec{B} \qquad \text{and} \qquad \mathcal{L}_s = \frac{1}{M_s}\phi_s(E^2 - B^2),$$

where M_a and M_s are the inverse coupling constants.

Depending on the mass of the hypothetical particle with respect to the photon energy, both birefringence and dichroism will be induced [3]. Here we will only report the induced birefringence. The induced birefringence in the pseudoscalar case, where $n^a_\parallel > 1$ and $n^a_\perp = 1$, and in the scalar case, where $n^s_\perp > 1$ and $n^s_\parallel = 1$, will be

$$|\Delta n| = n^a_\parallel - 1 = n^s_\perp - 1 = \frac{B^2_{\rm ext}}{2M^2_{a,s}m^2_{a,s}}\left(1 - \frac{\sin 2x}{2x}\right), \tag{7}$$

where, in vacuum, $x = \frac{Lm^2_{a,s}}{4\omega}$, ω is the photon energy and L is the magnetic field length. The above expressions are in natural Heavyside-Lorentz units whereby $1\,\mathrm{T} = \sqrt{\frac{\hbar^3 c^3}{e^4 \mu_0}} = 195\,\mathrm{eV}^2$ and $1\,\mathrm{m} = \frac{e}{\hbar c} = 5.06 \cdot 10^6\,\mathrm{eV}^{-1}$.

Finally particles with millicharge ϵe will also induce birefringence through the Feynman box diagram [4-6]. In this case one must distinguish between fermions and spin 0 bosons. Defining a mass parameter $\chi \equiv \frac{3}{2}\frac{\hbar\omega}{m_\epsilon c^2}\frac{\epsilon e B_{\rm ext}\hbar}{m^2_\epsilon c^2}$ (S.I. units) for fermions the birefringence is

$$\Delta n^{Df} = \begin{cases} 3A_\epsilon B^2_{\rm ext}, & \text{for } \chi \ll 1, \\ -\frac{9}{7}\frac{45}{2}\frac{\pi^{1/2}2^{1/3}\left(\Gamma\left(\frac{2}{3}\right)\right)^2}{\Gamma\left(\frac{1}{6}\right)}\chi^{-4/3}A_\epsilon B^2_{\rm ext}, & \text{for } \chi \gg 1, \end{cases}$$

whereas for spin 0 bosons the birefringence is

$$\Delta n^{s0} = \begin{cases} -\frac{6}{4}A_\epsilon B^2_{\rm ext}, & \text{for } \chi \ll 1, \\ \frac{9}{14}\frac{45}{2}\frac{\pi^{1/2}2^{1/3}\left(\Gamma\left(\frac{2}{3}\right)\right)^2}{\Gamma\left(\frac{1}{6}\right)}\chi^{-4/3}A_\epsilon B^2_{\rm ext}, & \text{for } \chi \gg 1. \end{cases}$$

The best limit set today on magnetic induced vacuum birefringence at 95% c.l. [7] is

$$\Delta n^{(\mathrm{PVLAS})} < 4.6 \cdot 10^{-20}. \tag{8}$$

2. – Method

The PVLAS experiment, with a new setup being currently mounted at the Physics Department of the University of Ferrara and INFN section, Ferrara, Italy, has the goal of detecting for the first time magnetic vacuum birefringence by measuring the ellipticity Ψ acquired by a linearly polarized beam of light when traversing a magnetic field perpendicular to the propagation direction:

$$\Psi = \pi \frac{L_{\rm eff}\Delta n}{\lambda}\sin 2\vartheta, \tag{9}$$

where $L_{\rm eff}$ is the effective path length within the birefringent region with birefringence Δn, λ is the wavelength of the light traversing it and ϑ is the angle between the magnetic field and the light polarization.

To maximize the induced ellipticity the magnetic field region must be as long as possible, the magnetic field as intense as possible and the wavelength small. Finally the expected ellipticity must be compared to the different noise sources present and to the maximum available integration time. Experimentally $L_{\rm eff}$ can be made very long by using a very high-finesse Fabry-Perot cavity. Given a birefringent region of length L the effective path length is $L_{\rm eff} = \frac{2\mathcal{F}}{\pi}L$. Today finesses $\mathcal{F} > 400000$ can be obtained.

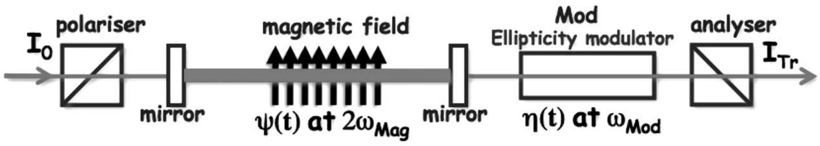

Fig. 1. – Scheme of the PVLAS ellipsometer.

Very high magnetic fields can be obtained with superconducting magnets but it is desirable to have a time-dependent induced ellipticity at a frequency as high as possible so as to stay away from DC and reduce $1/f$ noise. This can be done by either ramping the magnet, thereby changing Δn or by rotating the field direction, thereby changing ϑ. This makes superconducting magnets far less appealing than permanent magnets which, today, can reach fields of 2.5 T over volumes as those needed for PVLAS. Furthermore permanent magnets are relatively inexpensive, have no running costs and have 100% duty cycle allowing in principle very long integration times. Pulsed fields are another option for very intense and quickly varying fields [8] but duty cycle may be an issue.

The laser we are working with is a Nd:YAG laser emitting radiation at 1064 nm. Frequency doubled versions exist and could double the induced ellipticity but at the moment higher finesses have been obtained at 1064 nm.

A scheme of the ellipsometer is shown in fig. 1. The input polarizer linearly polarizes the laser beam of intensity I_0 which then enters the sensitive region defined by the Fabry-Perot cavity mirrors. The laser is phase locked to this cavity thus increasing the optical path length within the magnetic field by a factor $2\mathcal{F}/\pi$. After the cavity, to allow heterodyne detection the laser beam passes through a photo-elastic ellipticity modulator (PEM) which adds a known time dependent ellipticity $\eta(t) = \eta_0 \cos(\omega_{\rm Mod} t + \phi_{\rm Mod})$ to the beam. After the PEM the beam passes through the analyzer which selects the polarization perpendicular to the input polarization. A photodiode detects $I_{\rm Tr}$ and its Fourier spectrum is then analyzed. The intensity detected at the photodiode is therefore

$$I_{\rm Tr}(t) = I_{\rm out} \left| \imath\alpha(t) + \imath\eta(t) + \imath \left(\frac{2\mathcal{F}}{\pi}\right) \psi \sin\left(2\Omega_{\rm Mag} t + 2\phi_{\rm Mag}\right) \right|^2, \tag{10}$$

where we have also introduced $\alpha(t)$ which represents slowly varying spurious ellipticities due to the optical elements in the apparatus [9]. Therefore small ellipticities add up algebraically and the Fabry-Perot multiplies the single pass ellipticity $\psi \sin 2\vartheta$, generated within the cavity, by a factor $2\mathcal{F}/\pi$.

The presence of the beat frequency between $\eta(t)$ and $\Psi(t)$ generates a component at $\omega_{\rm Mod} \pm 2\Omega_{\rm Mag}$ and identifies an induced ellipticity within the Fabry-Perot cavity.

The apparatus being assembled in Ferrara has two 92 cm long permanent dipole magnets characterized by $\int B^2 {\rm d}l = 11\,{\rm T}^2{\rm m}$ which will rotate at an angular velocity of $\Omega_{\rm Mag} = 10\pi$ rad/s and a cavity with finesse $\mathcal{F} > 400000$. The reason for having two magnets instead of a single longer one is to be able to make zero measurements. By orienting the magnetic fields perpendicularly to each other the ellipticity induced by one magnet is cancelled by the second. One of the important characteristics is that the entire optical setup will be on one single optical bench thus strongly reducing seismic noise.

A test setup was built with two small 20 cm long, 2.3 T rotating magnets to understand and verify our design and understand whether it was possible to reach the required sensitivity necessary to detect for the first time vacuum magnetic birefringence with a reasonable integration time. A picture of the smaller test setup is shown in fig. 2. Results

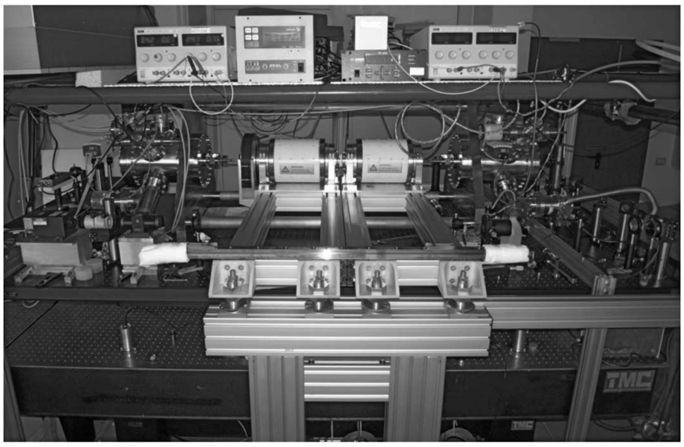

Fig. 2. – Photograph of the small test ellipsometer.

have been promising [7]. Furthermore the subtraction of the effects of the two magnets was also demonstrated using the Cotton-Mouton effect.

With this small apparatus we were able to improve by a factor ~ 2 the previous limits [10] on magnetic-induced vacuum birefringence reported in eq. (8) and a limit on A_e at 95% c.l. [7]

$$A_e^{(\mathrm{PVLAS})} < 2.9 \cdot 10^{-21}\,\mathrm{T}^{-2}. \tag{11}$$

With our new experimental parameters the induced ellipticity Ψ_{QED} will be

$$\Psi_{\mathrm{QED}} = \frac{2\mathcal{F}}{\pi}\frac{\pi 3 A_e B_{\mathrm{Ext}}^2 L}{\lambda} = 3.2 \cdot 10^{-11} \tag{12}$$

We hope to achieve an ellipticity sensitivity of $\Psi_{\mathrm{sens}} = 2 \cdot 10^{-8}\ 1/\sqrt{\mathrm{Hz}}$ [11]. This would lead to a first measurement of vacuum magnetic birefringence in $(\Psi_{\mathrm{sens}}/\Psi_{\mathrm{QED}})^2 = 103$ hours.

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