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Vacuum Magnetic Birefringence: QED & WISPS

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Abstract:

We propose to combine state of the art optical instrumentation with very high pulsed magnetic fields to study magneto-optical phenomena in the quantum vacuum.
Our goal is to realize the first ever measurement of the linear magnetic birefringence of vacuum (VMB) which corresponds to a variation in the velocity of light depending on its polarisation in the presence of transverse magnetic field. In the framework of the standard model this corresponds to test precisely Heisenberg-Euler Lagrangian describing photon-photon interactions.
The study of photon propagation inside a transverse magnetic field can also test physics beyond the standard model. In particular, photons in a magnetic field are predicted to oscillate into weakly interacting sub-eV particles (WISPs), such as the Axions. The VMB measurement that is proposed in this contribution will also push further the low-energy frontier of particle physics. A frontier yet rarely explored.

As an input to the European Particle Physics Strategy, we propose to combine state of the art optical instrumentation with very high pulsed magnetic fields to study magneto-optical phenomena in the quantum vacuum, i.e. the experimental proof of the magneto-optical properties of quantum vacuum [BMV_2013].
Our goal is to realize the first ever measurement of the linear magnetic birefringence of vacuum (VMB) which corresponds to a variation in the velocity of light depending on its polarisation in the presence of transverse magnetic field. This is one of the very rare macroscopic manifestations of QED vacuum energy that is understood to be permeating our universe, increasing the rate of expansion of the universe, and is one of the natural explanations of the dark energy that accounts for 73% of the total mass-energy of the universe.
The linear magnetic birefringence of vacuum is predicted by QED theory, but has not yet been observed. Its observation will be the first evidence of a macroscopic non-linear optical effect in vacuum and it will correspond to one of the last remaining tests of QED concerning the photon itself. So far, QED has been tested in bound systems like in the case of the Lamb shift of the hydrogen atom, or in isolated charged particles like in the case of the (g-2) of the electron.
Thanks to existing high magnetic field facilities (including our laboratory, the Laboratoire National des Champs Magnétiques Intenses (LNCMI) in Toulouse, France) this domain based on the use very high magnetic fields has made big progresses in recent years [Battesti_2018]. Seeking to observe vacuum magnetic birefringence for the first time, an experimental set-up (the BMV experiment) based around an intense pulsed magnetic field in conjunction with a high-finesse Fabry-Perot cavity currently operational at the LNCMI. Our magnetic field generation is unique in the world and our Fabry-Perot cavity one the most challenging ever realized.

As reviewed in ref. [Battesti_2018], the race to be the first to observe such a QED prediction is worldwide. At the moment, the experiment which is the closest to observation is based in Ferrara, Italy, PVLAS collaboration, while OVAL collaboration has been recently put forward in Japan. Many other proposals exist; some of them based in the most important particle physics laboratories like CERN and DESY [BMV_2013], [Battesti_2018]. Very recently, the observed polarisation of X rays coming from an isolated neutron star has been interpreted as a possible proof at the existence of vacuum magnetic birefringence [Mignani_2017]. Even if the interpretation has recently been questioned [Capparelli_2017], this illuminates the far reaching importance of such a measurement, even to the astrophysics field.

In this contribution, we propose to go beyond a simple observation of the effect and to achieve a measurement that advances the frontier of vacuum magneto-optics, providing a precise test of non-linear electrodynamics [Fouche_2017] and making a significant contribution to quantum electrodynamics and to physics beyond the standard model.

QED test of the photon itself:
Quantum electrodynamics (QED) has been widely tested in bound systems like in the hydrogen atom [Hydrogen], or in charged particles like in the case of the (g-2) of the electron [Gabrielse], and QED theory is assumed to be very well proven. However, recent measurements of the charge radius of the proton using muonic hydrogen shows that this value differs by several standard deviations from what is expected [Muonic_H].
Furthermore, in these tests one observes the interaction at the microscopic level between the self-energy of the vacuum and the electron. QED can also be tested with the study of the interaction between quantum vacuum fluctuations and a real photon. In the framework of the standard model, as a particular case of non-linear electrodynamics [Fouche_2017], this kind of interaction is described by the effective Lagrangian L_{HE} established in 1935 and 1936 by Kochel, Euler and Heisenberg [L_HE]. For weak fields, L_{HE} can be written as:

$$L_{\mathrm{HE}} = L_0 + L_{\mathrm{EK}}$$

with $L_0 = \frac{1}{2}\left(\varepsilon_0 E^2 + \frac{B^2}{\mu_0}\right)$ the classical Maxwell Lagrangian

and $L_{\mathrm{EK}} = \frac{2\alpha^2\hbar^3}{45 m_e^4 c^5}\varepsilon_0^2\left[(E^2 + c^2B^2)^2 + 7c^2\left(\vec{E}.\vec{B}\right)^2\right]$ the first non linear correction

where ε_0 is the permittivity of vacuum, μ_0 is the magnetic constant, m_e is the electron mass, c is the speed of light in vacuum, $\hbar$ is the Planck constant over 2π, and α is the fine structure constant. Thanks to the constitutive equations, we have:

$D = \frac{\partial L}{\partial E} = \varepsilon_v \mathrm{E}$ $\qquad H = -\frac{\partial L}{\partial B} = \frac{B}{\mu_v}$,

In this effective approach, vacuum is treated as a standard medium, for which one can define macroscopic properties: a permittivity ε_v and a permeability μ_v [BMV_2013]. A vacuum therefore acquires a polarization or a magnetization when an external electric or magnetic field is applied. Thus, like the case of a standard non-linear medium, many non-linear optical processes in vacuum can be predicted. Nevertheless, due to their minute size, none of these effects have ever been observed with low energy photons. Some of them, like Delbrück scattering and photon splitting in a field of a nucleus, have been observed using gamma rays [BMV_2013] but with an uncertainty which precluded any test of the Heisenberg-Euler Lagrangian. As far as photon-photon scattering [BMV_2013] is concerned, very recently ATLAS collaboration announced the observation of it [ATLAS2017], again without a precise verification of predictions resulting from the Heisenberg-Euler Lagrangian but putting limits on the Born-Infeld electrodynamics (see [Akmansoy_2019] and ref. within).

The goal of our input is to test for the first time the Heisenberg and Euler Lagrangian through the measurement of one of its non-linear optical prediction: the magnetic linear birefringence of quantum vacuum. This effect, also known as the Cotton-Mouton effect, corresponds to an index of refraction, $n_{//}$, for light polarized parallel to the transverse magnetic field B that is unequal to the index of refraction, $n_{\perp}$, for light polarized perpendicular to the magnetic field. For symmetry reasons, the difference $\Delta n = n_{//} - n_{\perp}$ is proportional to B^2 [BMV_2013]: $\Delta n = n_{//} - n_{\perp} = k_{\mathrm{CM}} B^2$

This is a macroscopic consequence of the non-linearity of vacuum resulting from the polarization of the vacuum itself by an applied magnetic field. At the lowest orders in the fine structure constant, Δn can be written as [kCM_Theory]:

$$k_{\mathrm{CM}} = \frac{2}{15}\frac{\alpha^2\hbar^3}{m_e^4 c^5 \mu_0}\,[T^{-2}], \text{ for the main term} \qquad (1)$$

$$k_{\mathrm{CM}} = \frac{2}{15}\frac{\alpha^2\hbar^3}{m_e^4 c^5 \mu_0}\left(1 + \frac{25}{4\pi}\alpha\right)[T^{-2}], \text{ with the first radiative correction.} \qquad (2)$$

The α^3 term corresponds to the lowest order radiative correction to the main term. Its value is about 1.5% of the α^2 term. Using the 2010 CODATA recommended values for the fundamental constants, previous equation gives $k_{\mathrm{CM}} = (4.031699 \pm 0.000002) \times 10^{-24}\ [\mathrm{T}^{-2}]$.

As we see, the error due to known precision of fundamental constants is negligible compared with the difference resulting from the first order QED radiative correction. Thus the observation and measurement of k_{CM} corresponds to a pure test of the Heisenberg and Euler Lagrangian. This measurement is one of the last remaining tests of QED.

Testing physics beyond the standard model:

As shown in [Fouche_2017], when working in the more general framework of non-linear electrodynamics, such a test corresponds to a verification of a general class of effective Lagrangians, in which the Heisenberg-Euler one is a special case.

Thus, the study of photon propagation inside a transverse magnetic field can also test physics beyond the standard model. In particular, photons in a magnetic field are predicted to oscillate into axions [BMV_LULI]. This hypothetical particle has been predicted to solve the "strong CP problem" [Axion_CP] and it could be a possible constituent of dark matter [Axion_DarkMatter]. The conversion of photons into axions in a magnetic field results in a change of the optical polarisation [Maiani]. A Vacuum Magnetic Birefringence measurement will also make an important contribution to the search for axions. By improving the sensitivity of such a setup to the values necessary to observe the effect due to the quantum vacuum, we also widen the mass and coupling constant range tested by experiments for axions to a level not yet achieved by terrestrial experiments in a wide mass range. Limits obtained in this way do not depend on any physical model and are therefore more reliable than limits obtained from astrophysical observations which depend on assumptions on the properties of their celestial sources. As no theoretical consensus exists on the parameters of the axion, enlarging this range will increase the chance of an observation of this elusive particle.

In more general terms, as shown in ref. [Jaeckel2010], very weakly interacting sub-eV particles (WISPs), for example, axionlike particles (ALPs) but also hidden matter particles, may lead to observable effects in experiment looking for vacuum magnetic birefringence. As a matter of fact, this will push further the low-energy frontier of particle physics [Jaeckel2010]. A frontier yet rarely explored.

Experimental methods:

As previously discussed, the existence in the vacuum Cotton-Mouton effect has been predicted, but has yet escaped observation. Several groups around the world have attempted to measure it, but so far without success. The reason is simply the predicted size of the effect: $k_{\mathrm{CM}} = 4\times10^{-24}\,\mathrm{T}^{-2}$. This represents an enormous experimental challenge!
The principle of the experiment is to measure the ellipticity induced in a linearly polarized laser field by the presence of a transverse external magnetic field. A high finesse optical cavity is added in order to increase the optical path in the field. The acquired ellipticity, when the angle between light polarisation and the magnetic field B is set to 45°, is given by [BMV_2008]:

$$\Psi = \frac{2F}{\lambda} k_{\mathrm{CM}} B^2 L, \quad (3)$$

where F is the cavity finesse, λ is the laser wavelength and L is the optical path in the magnetic region. In order to have an induced ellipticity as high as possible, the magnetic field and the optical cavity are the two critical parameters to be optimized. This elegant detection scheme has been implemented by several groups around the world as presented in [Battesti_2018].

In contrast to other experiments chasing the measurement, our BMV group has proposed to use pulsed high magnetic fields, promising a large jump in sensitivity. In 2014, we reached the highest sensitivity reported at that time by any groups around the world [BMV_2014], with $k_{\mathrm{CM}} < 8 \times 10^{-21}\,\mathrm{T}^{-2}$ at 3σ with about 100 pulses. It corresponds to a k_{CM} sensitivity per pulse of 2.7×10^{-20} at 1σ and an ellipticity sensitivity of 1.5×10^{-7} per pulse at 1σ. This first-generation setup has finally allowed us to understand the main instrumentation limits and realize improvements that are needed to reach the final goal: a better overall stability of the experiment, a higher magnetic field and a better control of the systematic effects.

Currently, our group is ready to take data with a new generation experiment based on a more powerful magnet and an optical setup designed taking advantage of what we learned thanks to our first version. We will eventually observe the vacuum magnetic birefringence with a signal to noise at the unitary level. There is therefore space for an improved version of such an experiment whose goal is not simply to observe the effect, but to have a sensitivity to allow us to test the first radiative correction to the effect.

Our experimental setup is described in Refs. [BMV_2008, BMV_2011]. Briefly, as shown on Fig. 1, a linearly polarized Nd:YAG laser (λ = 1064 nm) is injected into the high finesse Fabry-Perot cavity consisting of the mirrors M_1 and M_2. The laser frequency is locked to the cavity resonance frequency using the Pound-Drever-Hall method. To this end, the laser propagates through an electro-optic modulator (EOM) creating control sidebands. The beam reflected by the cavity is then analyzed on the photodiode Ph_r. This signal is used to drive the acousto-optic modulator (AOM) for a fast control of the frequency difference between the laser and the cavity resonance. The piezo and peltier elements of the laser is then used for a slow frequency control and to maintain the AOM around its central frequency. Coils creating the magnetic field are placed between the cavity mirrors.

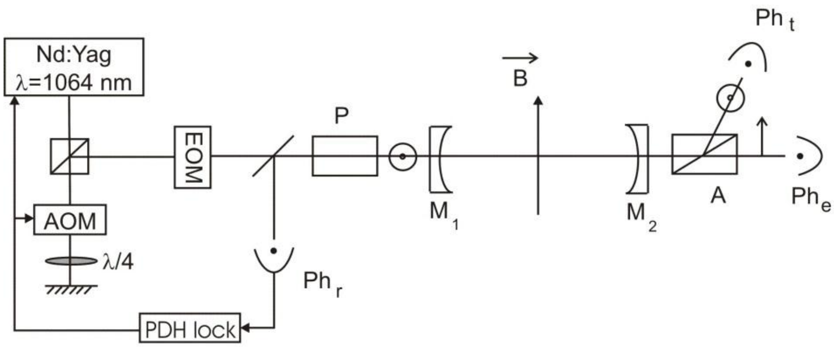

Fig. 1. Experimental setup of the BMV project.

Before entering the Fabry-Perot cavity light is precisely polarized by the polarizer P. The beam transmitted by the cavity is then analyzed by a second polarizer, A, crossed at maximum extinction. In our experiment, we have chosen to extract both polarisations: parallel and perpendicular to P, improving the sensitivity. The extraordinary ray is detected by the photodiode Ph_e, while the ordinary ray is detected by photodiode Ph_t. Both signals are used simultaneously in the data analysis as following:

$$\frac{I_e(t)}{I_{t,\text{filtered}}(t)} = \sigma^2 + [\Gamma + \Psi(t)]^2, \;\; \sigma^2 + \Gamma^2 + 2\Gamma\Psi(t) \text{ for } \Psi << \Gamma. \quad (4)$$

where σ^2 is the polarizer extinction ratio, Γ is the static ellipticity induced on the linearly polarized laser beam by the phase anisotropy of the cavity mirrors and Ψ is the ellipticity induced by the external magnetic field and proportional to B^2_{filtered}. $I_{t,\text{filtered}}$ and B^2_{filtered} are calculated from I_t and B^2 taking into account the cavity filtering as explained in Ref. [BMV_2010]. To extract from Eq. (4) the ellipticity Ψ which depends on the magnetic field, the sign of Γ must be controlled. This sign is obtained by measuring the Cotton-Mouton effect in nitrogen or in helium where the sign of the birefringence is known.

Our choice for the magnetic field has been to reach a B^2L having a B as high as possible with a L as small as possible to set-up a low noise optical experiment. The only way to produce very high magnetic fields is to use high current flowing into a coil. At the LNCMI in Toulouse, France, which is a laboratory specialized in pulsed magnetic fields, we have designed and tested a new geometry of coils, the so called X-coil. The coil properties are explained in Ref. [BMV_XCoil]. As with conventional pulsed magnets, the coil is placed in a liquid nitrogen cryostat to limit the consequences of heating. This cryostat is mechanically decoupled from the vacuum tube which passes through it.

A first version of X-coil reached a maximum field of 14.3 T with a pulse duration of 8 ms and a rise time of 2 ms. An improved X-coil magnet, called XXL-coil, has been successfully tested, giving a B^2L of more than 300 T^2m at the maximum field near the breaking point. The magnetic field as a function of time as well its profile along the longitudinal axis, which corresponds to the axis of propagation of the light, are shown in Fig. 2.

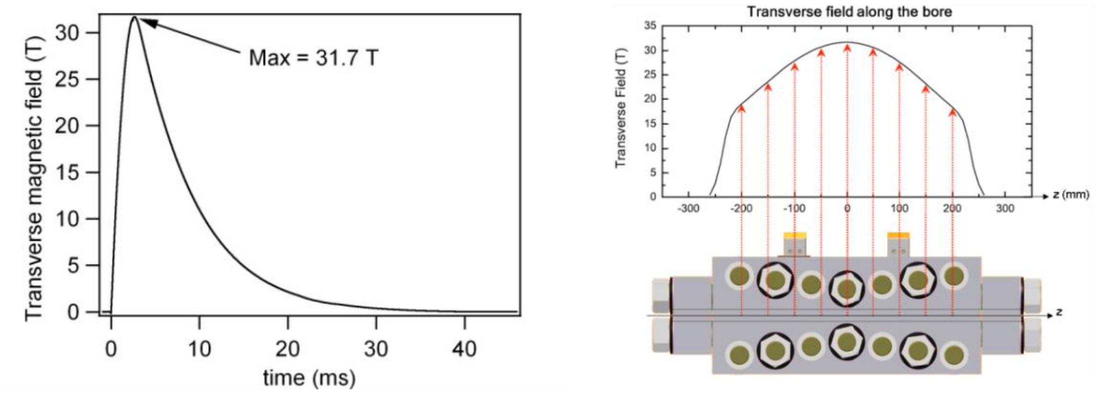

Fig. 2. XXL-Coil Left: magnetic field pulse of the XXL-Coil as a function of time. Right: measured magnetic field profile along the longitudinal axis.

Currently, a new version of a pulsed magnet for our application is under test. It is expected to reach a level of B^2L comparable with the one provided by the XXL-Coil with the advantage of operating at room temperature.

As shown by Eq. (2), we need a finesse *F* as high as possible with a large cavity length L_c to be able to put between the cavity mirrors as much coil as possible (large L), but still on a table-top experiment. The important parameter is thus FL_c. It is inversely proportional to the cavity linewidth: $\Delta\nu = c/2L_cF$ and proportional to the cavity quality factor: $Q=2\nu_{laser}FL_c/c$. We thus need a large FL_c, a high Q and a small $\Delta\nu$.
The length of our cavity is L_c=2.3 meters corresponding to a free spectral range of 65 MHz. Since the beginning of our project, the IN2P3 Laboratoire des Matériaux Avancés (LMA) of Villeurbanne, France has been in collaboration with us, being in charge of the realization of the very high finesse mirrors for our Fabry-Perot cavity. As these mirrors are very sensitive to contamination, our current experiment is necessarily housed in a clean room. Thanks to the know-how and experience at LMA, we have at our disposal mirrors with losses below 10 ppm reaching a finesse of 529 000 which corresponds to a cavity linewidth of about 124 Hz and a quality factor of 23×10^{11}.

Thanks to two ANR contracts obtained in the past and the LNCMI support, our BMV experiment is operational and we are confident that it will reach a unity signal to noise in the near future and that these experimental parameters will eventually allow us to observe the effect … but, how to go further and measure VMB to a higher precision?

The increase in the signal to noise ratio is achieved on two fronts. We propose to increase the expected signal by increase magnetic field and installing several coils in series, pulsed in parallel. Simultaneously, our efforts to decrease the noise will take advantage of the suspension technology. The move to suspended optics will reduce the vibration induced mirror birefringence noise, the leading noise source in the instrument [Hartman_2017]. Finally, intrinsic mirror birefringence must be understood and mitigated. To this purpose, the competences and continued collaboration with the LMA laboratory are a necessary component.

This proposed research has strong significance to research fields ranging from astrophysics to physics beyond standard model, while passing through standard QED. It has also a non-negligible technological impact resulting from the R&D of pulsed magnets and high finesse dielectric mirrors.

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