Vacuum Magnetic Birefringence

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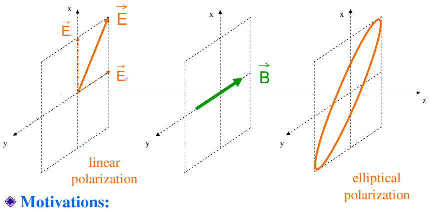
Introduction

◈ Magnetic birefringence or Cotton-Mouton effect



- of standard media
  known and studied since 1901
- of vacuum
  predicted in the 70^{ies}, but never experimentally observed

◈ Motivations:

- ◈ First evidence that vacuum is a non linear optical medium
- ◈ QED of photon R. Battesti and C. Rizzo, *Rep. Prog. Phys.* **76**, 016401 (2013)
- ◈ Observation of dark matter in terrestrial laboratory : axions, chameleons,…

◈ Ellipticity:

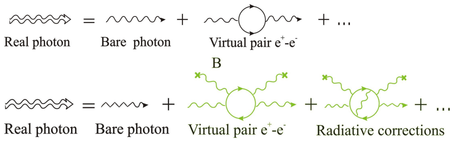
$$\Psi_{\text{QED}} = \frac{\pi}{\lambda}\left(\frac{2F}{\pi}\right)k_{\text{CM}}B^2L_B\sin(2\theta)$$

◈ Expected goals:

- ◈ $F \sim 1\,000\,000$
- ◈ $B^2\,L_B > 600$ T² m

$$\Psi_{\text{QED}} \approx 5\times10^{-9}$$

Theory



Without external field: Real photon = Bare photon + Virtual pair e$^+$-e$^-$ + …

With external field B: Real photon = Bare photon + Virtual pair e$^+$-e$^-$ + Radiative corrections + …

◈ Propagation of light in quantum vacuum in the presence of a magnetic field B

Vacuum is **Lorentz** and **CPT invariant**.

Effective **Lagrangian:**

$$\mathcal{L} = \frac{1}{2}F + aF^2 + bG^2 + \ldots \quad \text{where } F = \left(\varepsilon_0 E^2 - \frac{B^2}{\mu_0}\right) \quad \text{and} \quad G = \sqrt{\frac{\varepsilon_0}{\mu_0}}\left(\vec{E}.\vec{B}\right)$$

Configuration: $\begin{cases}\vec{E} = \vec{E}_\gamma \\ \vec{B} = \vec{B} + \vec{B}_\gamma\end{cases}$ $\vec{B}_\gamma, \vec{E}_\gamma$ photonic field, wave vector $\vec{k}$; $\vec{B} \perp \vec{k}$ applied magnetic field with $B >> B_\gamma, \frac{E_\gamma}{c}$

Kochel, Euler, Heisenberg (1935):

$$\Delta n = \frac{2}{15}\frac{\alpha^2\hbar^3}{m_e^4c^5}\left(1 + \frac{25}{4\pi}\alpha\right)\frac{B^2}{\mu_0}$$

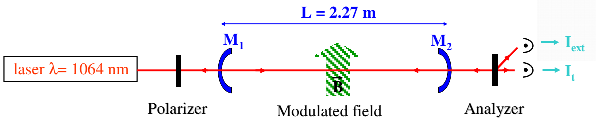
$$\Delta n = k_{\text{CM}}B^2$$

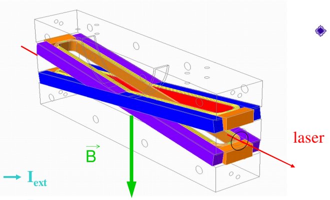
$$k_{\text{CM}} = 4\times10^{-24}\ \text{T}^{-2}$$

Experimental Setup

◈ Present experimental parameters:

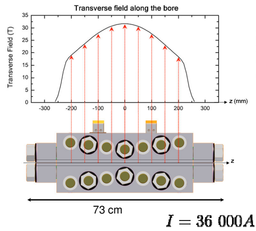
- ◈ **Nd:YAG laser** λ =1064 nm
- ◈ **pulsed magnetic field** $B_{\text{max}} = 6.5$T,
  $B^2L_B \approx 6$ T^2.m

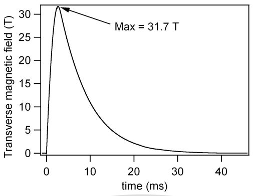




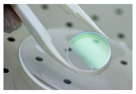
XCoil

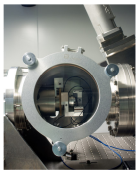
◈ New prototype of compact coil: 30 T transverse magnetic field

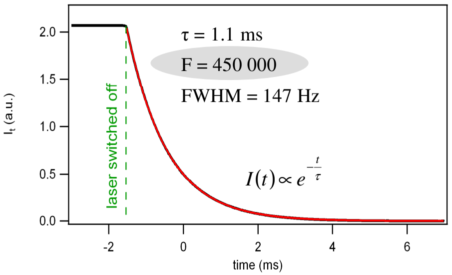




$I = 36\ 000A$ $B^2L = 300\ T^2m$







VIRGO:
1 000 Hz
LIGO:
160 Hz

NB: Magnets removed from light path

R. Battesti *et al., Eur. Phys. J. D,* **46**, 323 (2008)
P. Berceau *et al., Phys. Rev. A,* **85**, 013837 (2012)

Signal analysis

$$\frac{I_{\text{ext}}(t)}{I_{\text{t,f}}(t)} = \sigma^2 + [\Gamma + \Psi(t)]^2 + [\varepsilon + \theta_{\text{F}}(t)]^2$$

$$Y(t) = \frac{I_{\text{ext}}(t)/I_{\text{t,f}}(t) - \text{DC}}{2|\Gamma|} = \gamma\underbrace{\Psi(t)}_{}+\gamma\frac{\overbrace{|\varepsilon|\theta_{\text{F}}(t)}^{\text{B}}}{|\Gamma|} + \frac{\overbrace{\Psi^2(t)}^{\text{B}^4}}{2|\Gamma|} + \frac{\theta_{\text{F}}^2(t)}{2|\Gamma|}$$

◈ Variable parameters:

- ◈ **sign of Γ** : can be switched by rotating the mirrors
- ◈ **direction of $\vec{\text{B}}$**

◈ 4 series of shots: $Y_{>>}$, $Y_{><}$, $Y_{<<}$, $Y_{<>}$

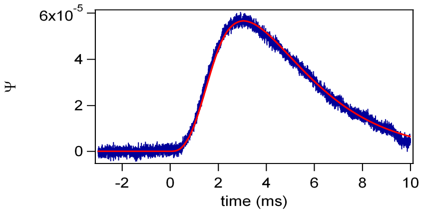
Sign of Γ — Direction of $\vec{\text{B}}$

◈ **Linear combinations to extract Ψ**

Last results

◈ Measurement of Cotton-Mouton effect of helium

(0.5 atm, 20 °C)

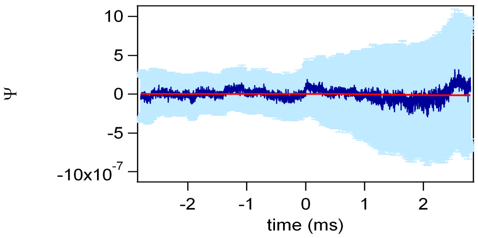


$$k_{\text{CM, theory}} = 2.24\times10^{-16}\ \text{T}^{-2}.\text{atm}^{-1}$$

$$\boxed{k_{\text{CM}} = (2.19 \pm 0.12)\times10^{-16}\ \text{T}^{-2}.\text{atm}^{-1}}$$

◈ Vacuum measurements

average of about 100 pulses



$$\boxed{k_{\text{CM}} = (-7.4 \pm 8.7)\times10^{-21}\ \text{T}^{-2}}$$

at 3σ confidence level