PROCEEDINGS OF SCIENCE

Polarimetry for Vacuum Magnetic Birefringence

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A presentation of a novel modulation scheme for the measurement of Vacuum Magnetic Birefringence in the low energy regime which utilizes a high frequency rotating magnetic field.

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1. Introduction

Following the formulation of Quantum Electrodynamics (QED) in the early 1930s, the classical theory of electromagnetic radiation was modified to incorporate the non-linear dynamics of electromagnetic fields. Euler-Kockel-Heisenberg derived a new Lagrangian [1–3] which describes the vacuum as a nonlinear anisotropic medium, with birefringence:

$$\Delta n = n_{\perp} - n_{\parallel} \approx 4 \times 10^{-24} [1/\mathrm{T}^2] \neq 0 \tag{1}$$

Under the influence of a magnetic field. This effect is known as vacuum magnetic birefringence, which induces a phase delay, φ, between two orthogonal components of linearly polarized light leading to an ellipticity, ψ:

$$\psi = \frac{\varphi}{2} \sin 2\theta = \frac{\pi \Delta n L}{\lambda} \sin 2\theta \tag{2}$$

where L is the length of the magnetic field in which the light of wavelength λ propagates, and θ is the angle between the direction of polarization of the light and the external magnetic field.

2. Experimental Method

2.1 Background

The dominating noise source for previous birefringence measurements has been that of thermally driven intra-cavity noise investigated by the PVLAS group in reference [4]. Considering the main components limiting the sensitivity of VMB experiments highlights the importance of maximizing the strength of the B-field, the propagation length L, frequency f in which the VMB signal appears, and time integration T. The signal to noise ratio can be simplified to:

$$\mathrm{SNR} \propto |B|^2 \cdot L \cdot f^{0.8} \cdot \sqrt{T} \tag{3}$$

2.2 Electromagnet Modulation

We present a novel modulation scheme that employs a kHz rotating dipole magnetic field in combination with a polarimeter based on a Fabry-Perot cavity, utilizing a heterodyne readout technique. The core of the experiment consists of two 40 cm magnets arranged in a Halbach array configuration, generating a 1 Tesla dipole field at the center, designed and manufactured by Linz Center of Mechatronics. Although the magnets remain physically static, the dipole field is rotated at 1 kHz by pairs of electromagnet coils with alternating current. This rotation is sustained over an extended period to optimize time integration as in the Eq. 3. The implementation of this scheme is shown in Fig. 1.

2.3 Intrinsic Noise and Sensitivity

The limiting sensitivity of the polarimeter is determined by the intrinsic noise sources present in the apparatus: shot noise, dark current, Johnson noise, and relative intensity noise (RIN). Figure 2 shows these as a function of the modulation depth of the PEM, η_0, which highlights the most effective operating point of our experiment. The results presented in the figure lead to a minimum

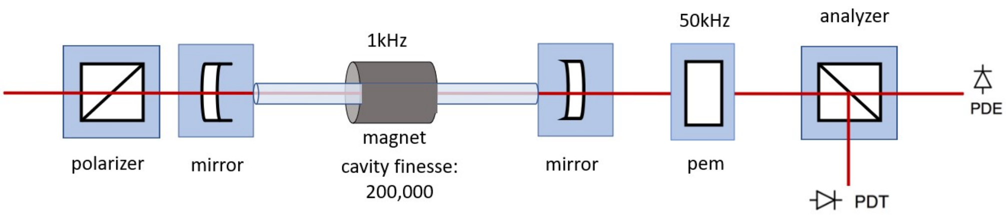

Figure 1: Simplified drawing of experimental setup. Light blue boxes indicate ultra high vacuum chambers connected via a vacuum tube. The red line is laser light. PEM is the photo-elastic modulator, and the analyzer a high extinction polarizer. PDE and PDT are the two photodiodes that measure the transmitted and extinguished light after the analyzer, where the former measures the induced ellipticity.

integration time of $T = 140$ days to reach an SNR $= 1$. The parameters used are displayed in Table 1, see Appendix.

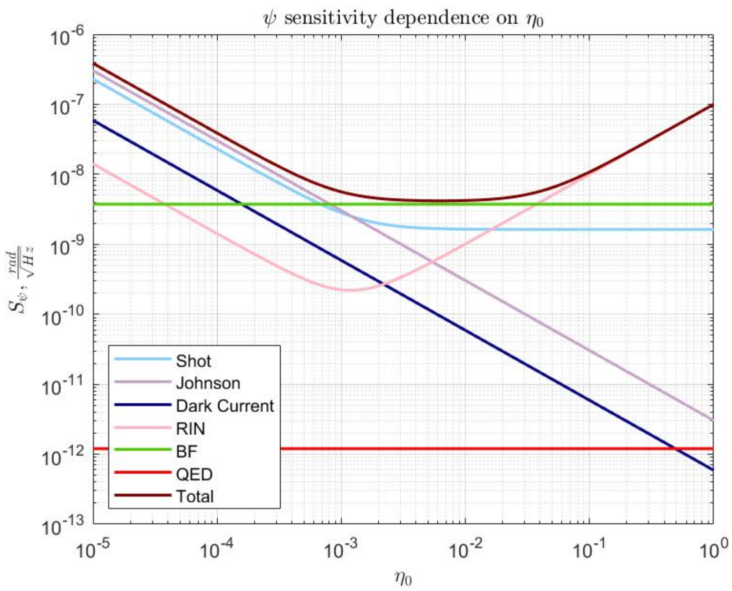

Figure 2: Intrinsic noise budget as a function of the modulation depth of the PEM. Bright red line marks the QED signal at $B = 1$ T, $L = 80$ cm, and finesse $\mathfrak{F} = 200,000$.

3. Conclusion

Vacuum Magnetic Birefringence (VMB) is a Quantum Electrodynamics (QED) effect first theorized in the early 1930s, which has yet to be detected despite many decades of experimental attempts. To mitigate the frequency-dependent birefringence noise originating from within the cavity, a kHz magnet modulation frequency was selected. The intrinsic noise sources indicate a minimum integration time of 140 days to reach the QED effect. This tabletop experiment is scheduled to be built at the Max Planck Institute for Gravitational Physics in Hanover, Germany, in the coming year.

4. Appendix

Parameter	**Value** K
Magnetic field, B	1 T
Length, L	0.8 m
Cavity finesse, $\mathfrak{F}$	200,000
PEM freq, ν_{PEM}	50 kHz
Magnetic field freq, $\nu_{B_{\text{ext}}}$	1 kHz
Temperature, T	300 K
Gain, G	10^6 V/A
Quantum efficiency, q	0.6 A/W
Intensity, I_0	0.1 W
Dark current, i_{dark}	25×10^{-15} A/$\sqrt{\text{Hz}}$
Extinction ratio, σ^2	10^{-7}
$N^{\text{RIN}}_{@50\text{ kHz}}$	$10^{-7}\ \frac{1}{\sqrt{\text{Hz}}}$

Table 1: Table of parameters planned to be used in the upcoming experiment.

5. Acknowledgments

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