All-Optical Vacuum Birefringence with PW-Class Lasers: Case Study for the ELI-NP Parameters

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The yet-untested predictions of quantum electrodynamics are the ones stemming from the non-perturbative regime described by the Heisenberg-Euler (HE) Lagrangian [1]. Among those predictions, one can mention light-by-light scattering [2], light splitting [3] and vacuum birefringence [4]. The latter has attracted a lot of attention, with magnetic field-based experiments performed or ongoing [5].

Following the proposal from reference [6], we elaborate on the feasibility studies for an interferometric, all-optical, Mach-Zehnder-based vacuum birefringence experiment. The idea of the experiment is based on a pump-probe configuration combining a 10 PW laser and a pulsed probe beam. As proposed in reference [7], for a counter-propagating geometry the ideal probe pulse duration is

$$\tau_p = \frac{2\pi w_0^2}{\lambda_L c}, \tag{1}$$

where w_0 denotes the radius of the pump laser at focus and λ_L its central wavelength. If $w_0 \sim 3 - 5\mu$m, the optimal range of probe pulse duration is $\tau_p \sim 235 - 654$ fs. Assuming thus a shot-noise scaling for the interferometric phase sensitivity, the minimal probe power needed for a successful detection is

$$P_p \geq \frac{hc^2 \lambda_L \lambda_p w_0^2}{8\pi c_{\|}^2 \Lambda_{EK}^2 \mathcal{E}_L^2} \approx 8.46 \cdot 10^8 \frac{\lambda_L[\mu\text{m}]\lambda_p[\mu\text{m}](w_0[\mu\text{m}])^2}{(\mathcal{E}_L[\text{J}])^2} \tag{2}$$

where λ_p denotes the central wavelength of the probe beam, $c_{\|} = 32$, $E_S = m^2c^3/e\hbar$, $\mathcal{E}_L$ is the pump laser pulse energy and $\Lambda_{EK} = \frac{\alpha}{90\pi\varepsilon_0 E_S^2} = \frac{2\alpha^2\hbar^3}{45m^4c^5} \approx 1.65 \times 10^{-30} \quad [\text{m}^3/\text{J}]$ is the vacuum nonlinearity coefficient introduced by the HE Lagrangian. For a 10 PW pump laser featuring an energy per pulse of $\mathcal{E}_L = 250$ J, we arrive at a minimum required probe power in the range $P_p \sim 52 - 144$ GW. These powers are readily available today for lasers having a pulse duration in the 100 fs – 1 ps range.

We discuss an experimental scheme able to implement the required pump-probe interaction geometry. In order to mitigate the undesired effect of timing jitter between the two lasers, we consider a probe beam pulse duration longer by a factor of $1.5 - 2$ relative to eq. (1). Thus, the pre- and post- interaction part of the probe pulse will be used to calibrate the "vacuum" signal.

With the Mach-Zehnder interferometer brought to its optimum working point, a QED-induced phase shift should translate into a detectable signal at its output.

References

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