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Laser-driven search of axion-like particles including vacuum polarization effects

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Abstract

Oscillations of photons into axion-like particles in a high-intensity laser field are investigated. Nonlinear QED effects are considered through the low energy behavior of the vacuum polarization tensor, which is derived from the Euler–Heisenberg Lagrangian in the one-loop and weak field approximations. The expressions obtained in this framework are applied to the configuration in which the strong background field is a circularly polarized monochromatic plane wave. The outcomes of this analysis reveal that, in the regime of low energy–momentum transfer, the axion field induces a chiral-like birefringence and dichroism in the vacuum which is not manifest in a pure QED context. The corresponding ellipticity and angular rotation of the polarization plane are also determined. We take advantage of such observables to impose exclusion limits on the axion parameters. Our predictions cover axion masses for which a setup based on dipole magnets provides less stringent constraints. Possible experimental scenarios in which our results could be tested are also discussed.

Keywords: Beyond standard model; Vacuum polarization; Laser fields; Axion-like particles

1. Introduction

The nonlinear vacuum of Quantum Electrodynamics (QED) is an illuminating laboratory for exploring physics beyond the framework of the Standard Model (SM) of fundamental interactions. Over the last few years there have been substantial efforts devoted to employ its

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unconventional properties in the search of a plausible but elusive pseudo-scalar particle known as the axion. This hypothetical Nambu–Goldstone boson emerges from the spontaneous breaking of the Peccei–Quinn symmetry and turns out to be a distinctive quantity within the solution to the strong CP problem [1–3]. It additionally conforms to the paradigm of axion-like particles (ALPs) closely associated with some extensions of the SM which naturally emerge from string compactifications [4,5]. Conceptually the ALPs encompass both scalar and pseudo-scalar bosons [6–8] being likely candidates for the dark matter of the universe [9–12]. Their conversion into an electromagnetic field is a long-standing prediction which has been frequently analyzed in a constant magnetic field [13–16]. In this external field configuration the absorption of a photon into a real ALP induces an attenuation of a probe laser beam. Since the amount of absorbed photons is different for each propagating mode the vacuum behaves as a dichroic medium. Simultaneously, in the presence of a external magnetic field, the ALP–photon coupling modifies the vacuum birefringence caused by the polarization of virtual electron–positron pairs [17–20]. Both phenomena have inspired polarimetric experiments in which indirect evidence of ALPs could be detected. Among the most significant collaborations are BFRT [21], PVLAS [22], BMV [23] and Q&A [24]. On the other hand, there exists another interesting mechanism of finding traces of the ALPs existence which relies on the photon regenerative property, commonly known as "Light Shining Through a Wall" [25–28]. This has been experimentally implemented in several collaborations such as ALPS [29,30], GammeV [31,32], LIPSS [33], OSQAR [34] and BMV [35,36]. However, despite the push to detect these particles, the results provided by both kinds of experiments are far from proving that the photon oscillations into ALPs occur. Instead, upper bounds on the unknown parameter of ALPs, i.e., coupling constant g and mass m have been established, as well as for other weakly interacting particles including paraphotons [37–41] and mini-charged particles [42–47]. The main difficulty in these experiments stems from the projected lightness of the ALPs and the weakness of their coupling constants, hence the detection of their tiny observable effects represents a huge technical challenge.

An optimal setup is necessary to overcome this obstacle. Very often the magnetic field strength $|\boldsymbol{B}|$ as well as its spatial extension ℓ is exploited to partially achieve this goal. Their combined effects, usually evaluated through the product $|\boldsymbol{B}|\ell$, facilitate the enhancement of observables associated with the mixing process as long as both quantities are increased. Frequently, in high-precision optical experiments, field strengths of the order of $|\boldsymbol{B}| \sim o(10^4\text{–}10^5)$ G are extended over lengths $\ell \sim o(10^2\text{–}10^3)$ cm so that $|\boldsymbol{B}|\ell \sim o(10^6\text{–}10^8)$ G cm. Although the incorporation of interferometric techniques has allowed to extend the interaction region up to macroscopically distances $\ell \sim o(10^3)$ m, the attainable laboratory values of $|\boldsymbol{B}|$ are not strong enough to manifest the desirable effects. Gradually, the technology of high-intensity lasers is proving to be an alternative tool as it can achieve much stronger field strengths $|\boldsymbol{B}| \sim o(10^9)$ G in a short space-extension of the orders of $\ell \sim o(1\text{–}10)$ μm allowing for the product $|\boldsymbol{B}|\ell \sim o(10^5\text{–}10^6)$ G cm. However, this tiny interaction region could be compensated for by the envisaged ultrahigh intensities at future laser facilities. Contemporary projects such as the Extreme Light Infrastructure (ELI) [48] and the Exawatt Center for Extreme Light Studies (XCELS) [49] are being designed to reach the unprecedented level of $|\boldsymbol{B}| \sim o(10^{12})$ G, an order of magnitude below the critical magnetic field of QED $B_c = 4.42 \times 10^{13}$ G, above which the superposition principle is no longer valid and the product $|\boldsymbol{B}|\ell \sim o(10^8\text{–}10^9)$ G cm exceeds by an order of magnitude the maximum value resulting from experiments driven by a constant magnetic field. This has raised hopes that nonlinear effects including vacuum birefringence [50,51], photon splitting [52], diffraction effects [53–58] and the spontaneous production of electron–positron pairs from the vacuum [59–61] may soon be within an experimental scope with purely laser-based setups. There