High-Intensity Probes of Axion-Like Particles

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With continuously increasing intensities, modern laser systems can become a valuable tool for the search for axions and axion-like particles. As conventional setups of axion searches cannot easily accommodate the usage of a high-intensity laser system, we propose a novel, purely laser-based setup in which the occurrence of a frequency shift is an observable for the axion-photon interaction.

1 Motivation

Optical probes of the axion-like particle (ALP) parameter space, such as polarimetric measurements or "Light-shining-through-walls" setups, are enhanced by applying strong external (electro-)magnetic fields B over a large spatial extent L. Conventionally, dipole magnets are used to modify the propagation of probe beams. But with the remarkable increase in available laser intensity over the past years, multi-terawatt laser systems have become competitive with dipole magnets in providing $B \times L$ and can be expected to eventually exceed them. Still, the limited temporal and spatial extent of pulsed high-intensity beams disfavors standard setups used for ALP search and requires different observables which are particularly useful for purely laser-based experiments. Such an observable can, e.g., be a diffraction pattern [1], or a frequency shift [2, 3]. The latter will be the subject of this contribution.

2 Photon-Axion dynamics

As we are interested in the effects of the nonlinear interaction of laser photons due to the presence of an axion or ALP, we start from the equations of motion for the two fields:

$$\partial_\mu \partial^\mu \phi + m^2 \phi - \frac{1}{4} g F_{\mu\nu} \tilde{F}^{\mu\nu} = 0 \tag{1}$$

$$\partial_\mu F^{\mu\nu} - g(\partial_\mu \phi)\tilde{F}^{\mu\nu} = 0 . \tag{2}$$

For the following discussion, we split the field strength tensor $F_{\mu\nu}$ into contributions of a probe field $F_{\mu\nu}^{\text{in}}$ and two external high-intensity beams $F_{\mu\nu}^{\text{ext}}$, and linearize in the probe field. Coupling to the first external beam in Eq. (1), the probe photons can be converted into ALPs, denoted by ϕ. Successively, by means of Eq. (2), the ALPs can be reconverted into photons through the second external field. For simplicity, the following discussion will be limited to a one-dimensional setup where the probe photons propagate along the positive z axis. Then, the above equations of motion can be solved using a Green's function approach [2, 4].

In order to motivate the findings for a purely laser-based setup we first review the probe photon dynamics for static or slowly varying external fields spanning a length L as e.g. provided by a dipole magnet. In this case, employing an incoming plane wave probe beam of frequency ω_{in} in Eq. (1) yields via Eq. (2) an outgoing wave that carries the original frequency ω_{in} after the intermediate propagation as an ALP, necessitating the use of a light-blocking wall or polarimetric measurements. In addition, the outgoing wave's amplitude picks up two factors of $\sin(\Delta k \frac{L}{2})/\Delta k$ with $\Delta k = -\omega_{\text{in}} + \sqrt{\omega_{\text{in}}^2 - m^2}$ arising in the conversion and back-conversion processes, respectively, causing it to be maximal at $\Delta k \simeq 0$. From this it follows that the ALP search with dipole magnets is most sensitive for small ALP masses, cf. also Fig. 2.

From another perspective, the sensitivity for small axion masses being maximal is related to momentum conservation as reflected by the requirement $\Delta k \simeq 0$ for both the photon-axion conversion and back-conversion process.

3   Photon-Axion conversion in high-intensity laser fields

From the preceding consideration it becomes obvious that employing lasers as external fields will modify the momentum balance as they carry a further frequency scale. This changes the sensitivity characteristics with respect to the ALP mass. Moreover, in accordance with energy conservation, the frequency of the outgoing photon will in general be modified. This happens in close analogy to the processes of sum-frequency generation (SFG) and difference-frequency generation (DFG) known from nonlinear optics. The frequency of the outgoing electromagnetic wave will be the sum or difference of the incident frequencies and, analogous to the phase matching conditions within SFG and DFG, the wave vectors of the external beams (being different in general) enter the requirements[1]
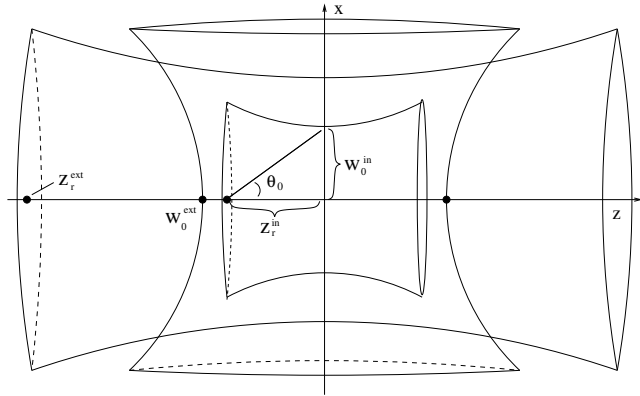

Figure 1: Overlap of Gaussian laser beams. The innermost probe beam is embedded into two external beams propagating orthogonally and transversally to it, respectively. The waist size w_0^{ext} as well as the Rayleigh lengths z_r^{in} and z_r^{ext} determine the extent of the beam foci.

$\Delta k \simeq 0$. In summary, we thus suggest the measurement of a frequency shift $\omega_{\text{out}} \neq \omega_{\text{in}}$ of probe beam photons as an observable of photon-ALP interaction, which is feasible for unsuppressed interaction amplitudes, i.e. $\Delta k \simeq 0$ for the conversion and back-conversion process. This perfectly accommodates the features of the high-intensity beam making the use of a light-blocking wall or polarimetric measurements superfluous. With hindsight, we choose a configuration in

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[1] Introducing high-intensity lasers as external fields changes also the functional form of the conversion amplitude since one has to employ a Gaussian beam form [5]. Also, the length scale L will be substituted by the natural spatial extent of Gaussian beams, being the waist size w_0 and the Rayleigh length z_r of the beams.

which the photon-axion conversion is mediated by an external beam of frequency $\omega_\perp$ propagating orthogonally to the z axis, while the back-conversion process from the ALP to a photon is due to a counter-propagating beam with $\omega_\parallel$, cf. Fig. 1.

Then, as within SFG and DFG, one obtains from Eq. (1) ALP partial waves carrying frequencies $\omega_{ax}^\pm = \omega_{in} \pm \omega_\perp$, while the corresponding 'phase matching condition' becomes

$$\Delta k_\perp^\pm = -\omega_{in} + \delta_T \sqrt{(\omega_{in} \pm \omega_\perp)^2 - m^2} \stackrel{!}{\simeq} 0 \ , \tag{3}$$

with $\delta_T = \pm 1$ in case of transmission and reflection of the ALP wave, respectively.

Above, $\Delta k_\perp^+ = 0$ is realized in the case of transmission (i.e. $\delta_T = +1$) for $m = m_\parallel \equiv \sqrt{\omega_\perp^2 + 2\omega_{in}\omega_\perp}$, whereas $\Delta k_\perp^- = 0$ cannot satisfy the requirement of a non-negative ALP frequency ω_{ax}. Thus, only the 'SFG solution' $\omega_{ax}^+ = \omega_{in} + \omega_\perp$ is kept in the following.

Note that, since the wave vector of the external $\perp$ beam has no component along z, it does not enter *explicitly* in the momentum conservation in Eq. (3). This is different for the back-conversion process mediated by the $\parallel$ beam. The outgoing electromagnetic partial waves now carry frequencies $\omega_{out} = \omega_{in} + \omega_\perp \pm \omega_\parallel$, whilst momentum conservation requires that

$$\Delta k_\parallel^\pm = -\sqrt{(\omega_{in} + \omega_\perp)^2 - m^2} + \delta_T(\omega_{in} + \omega_\perp \pm \omega_\parallel) \pm \omega_\parallel \stackrel{!}{\simeq} 0 \ . \tag{4}$$

As argued above, Eqs. (3) and (4) have to hold simultaneously for a feasible sensitivity while we demand $\omega_{out} \neq \omega_{in}$ as an observable for the photon-ALP conversion. Requiring positivity of all frequencies, it can be checked that this is only possible for DFG and transmission of the wave, i.e. $\delta_T = +1$ in Eq. (4). In particular, choosing $\omega_\perp = 2\omega_\parallel$, we see that $\Delta k_\parallel^- = \Delta k_\perp^+ = 0$ for axion masses $m = m_\parallel$ yielding $\omega_{out} = \omega_{in} + \omega_\parallel$. This constitutes an observable of the ALP-photon interaction[2]. As the resonant masses $m_\parallel$ and $m_\perp$ are of the same order of magnitude as the laser frequency scales being $\mathcal{O}(eV)$, purely laser-based searches are *complementary* to standard dipole setups. Of course, to facilitate the detection of the frequency shift requires ω_{out} to lie feasibly outside the spectral widths $\Delta\omega$ of all interacting beams.

At last, it is worth emphasizing that the condition $\omega_\perp = 2\omega_\parallel$ is in fact an enormous experimental advantage since second harmonic generation is a standard technique even for high-intensity lasers, thus requiring the employment of only *one* external high-intensity beam.

4　Discovery potential

An estimate of the ALP discovery potential for purely laser-based searches is given in Fig. 2, see [2] for details. Here, the black wedge-like curves and the black line correspond to a feasible setup at IOQ [8] employing the multi-TW class laser JETI as probe and the PW class laser POLARIS as external beam, which could be realized in the near future. For the estimate, single-photon detection is assumed for the frequency-shifted photons[3]. The wedge-like structures of the bounds around $m_\parallel$ and $m_\perp$ are a consequence of the fixed frequencies within the setup.

Using optical parametric amplification (OPA) for the probe beam, a larger range of the mass-coupling plane can be explored, as indicated by the black line. However, as OPA limits

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[2]In the discussed setting, the photon-ALP conversion can also be induced by the ($\perp$) oriented field and back-conversion can be due to the counter-propagating ($\parallel$) field as the interaction order is not assessable for synchronized pulses. The conversion process with the opposite order $\perp \leftrightarrow \parallel$ results in $\omega_{out} = \omega_{in} - \omega_\parallel$ for axion masses around $m_\parallel = 2\sqrt{\omega_{in}\omega_\parallel}$ and $\omega_\perp = 2\omega_\parallel$, thus defining a second 'resonant mass' besides $m_\perp$ [2].

[3]For higher photon statistics the number of shots N_{shot} can be increased ($\mathcal{O}(100)$ per day at IOQ [8]).

intensity, the sensitivity to the ALP coupling is decreased. Nevertheless, we see that a setup at IOQ could provide the strongest model-independent [6] bounds for ALP masses at $\mathcal{O}(\text{eV})$.

Even smaller ALP coupling values can potentially be probed at the future exawatt class facility ELI [7]. Already with single shot measurements it can be possible to almost complement the currently best laboratory bounds provided by ALPS [9] in the $\mathcal{O}(\text{eV})$ mass range as shown by the red dotted line in Fig. 2. In order to surpass even the CAST [10] bounds on solar axions, one would require $N_{\text{shot}} N_{\text{in}} \approx 10^{26}$ at ELI (dash-dotted line). This constitutes a rather ambitious aim, but would allow for a direct probe of the QCD axion parameter space (given as a yellow band in Fig. 2), making it a worthwhile task for the future.

5   Conclusions

The rapid increase in available laser intensity strongly suggests to investigate the potential of high-intensity lasers for axion and ALP search. As argued, a possible observable in this context is the measurement of a probe beam frequency shift. This is particularly useful since the limited temporal and spatial extent of the pulses disfavors conventional setups such as polarimetric measurements and Light-shining-through-walls. In summary, high-intensity probes of ALPs can constitute a new tool in the general quest [11] for weakly interacting slim particles.

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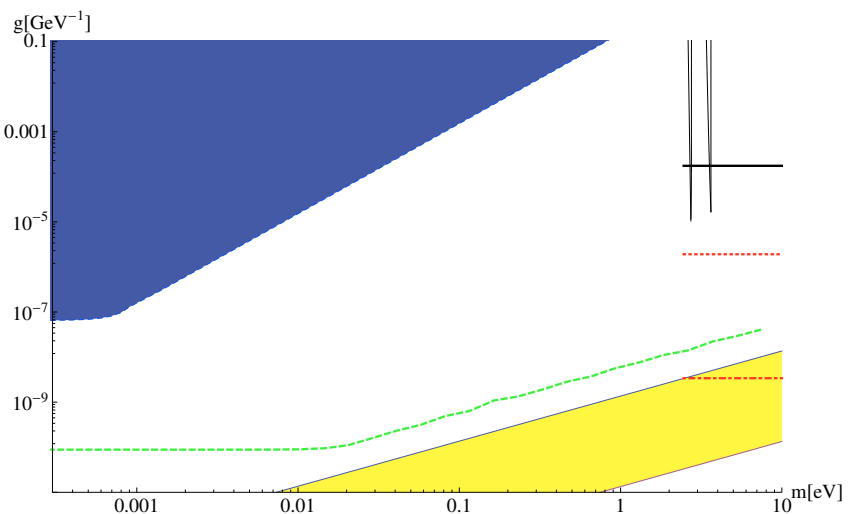[11] J. Jaeckel and A. Ringwald, arXiv:1002.0329 [hep-ph].

Figure 2: ALP exclusion bounds for ALPS [9] (blue-shaded area), and CAST [10] (green-dashed line) in comparison to a setup involving the laser systems available in Jena [8], denoted by black wedges. The black line indicates the principle exclusion bounds at this setup employing a conventional OPA system, while the red-dotted line gives an analogous estimate for ELI [7]. The red dot-dashed line suggests the requirements at ELI for entering the parameter regime of typical QCD axion models which are given by a yellow band.