Light-shining-through-wall searches for axion-like particles using laser-driven plasma

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Not all key questions in fundamental physics can be readily investigated using conventional high-energy particle collider technology, and modern developments in laser-plasma-based accelerator science offer a new perspective in the quest for physics beyond the Standard Model. In particular, alternative methods are required to search for novel low-mass particles with very weak coupling to ordinary matter. The QCD axion is probably the most celebrated example of such a particle; although it was introduced to explain the lack of CP violation in the strong interaction [1, 2, 3], interest in it as a cold dark matter candidate developed soon after it was proposed [4, 5, 6].

The QCD axion arises as a pseudo-Nambu-Goldstone boson of a broken global symmetry (the Peccei-Quinn symmetry); thus, the QCD axion is a natural feature of Grand Unified Theories. In particular, the predictions of string theory are replete with such particles [7]. The wider group are known as *axion-like particles* (ALPs), and they resemble the QCD axion in that they interact with ordinary matter and fields in a similar way to the QCD axion. However, their masses and coupling strengths differ from the QCD axion.

Over the last few decades, numerous experimental campaigns have been waged in an effort to detect the QCD axion and its ALP brethren. Although the most established approaches rely on astrophysical sources, a number of searches for ALPs have been developed in recent years that are based entirely in the laboratory (see Ref. [8] for a recent review). In particular, the canonical *light-shining-through-wall* (LSW) searches for ALPs [9] are based on ALP production from the interaction of a laser with a magnetic field on one side of a barrier opaque to photons. The ALPs propagate through the barrier, and convert back to photons in a magnetic field on the other side of the barrier.

To date, there is no definitive experimental evidence for the QCD axion or ALPs. However, the theoretical arguments for their existence are compelling, and it is worth exploring every available avenue in an effort to uncover them. Although much of the ALP parameter space has been constrained (see, e.g. Ref. [10]), there is room for new investigation. Our proposal [11] is to replace the section of a canonical LSW experiment in which the ALPs are generated by a laser-wakefield accelerator immersed in a static magnetic field (see Fig. 1). Our approach

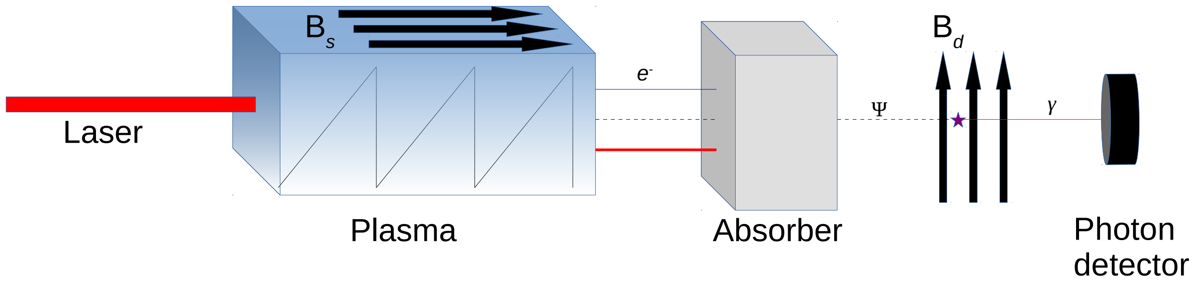

Figure 1: A novel LSW experiment in which a laser-driven non-linear plasma wave (indicated by a sawtooth) interacts with a static longitudinal magnetic field to produce ALPs (dashed line), energetic electrons (blue line) and intense photons (thick red line). Photons, electrons and ALPs emanate from the laser-driven plasma. The photons and electrons are absorbed downstream, whilst the ALPs penetrate the barrier/absorber and are converted to terahertz photons (thin red line) using a static transverse dipole field [11].

exploits the strong longitudinal electric field ($\sim 100\,\mathrm{GV\,m^{-1}}$) present in the wake behind a high intensity ($\sim 10^{19}\,\mathrm{W\,cm^{-2}}$), short ($\sim 2\,\mu\mathrm{m}$), laser pulse propagating through an underdense plasma. The plasma section of the laser-wakefield accelerator would be sited inside the bore, along the axis, of a solenoid generating a strong (e.g. $\sim 35\,\mathrm{T}$ [12]) longitudinal magnetic field.

The electromagnetic field configuration responsible for generating ALPs in our approach is very different to that used in the regular LSW experiments. In the standard LSW configuration, the majority of the ALP production arises through the product of the dynamical transverse component of the electric field of a laser and a static transverse magnetic field. However, in our approach the ALPs are essentially driven by the product of the quasi-static longitudinal component of the electric field of the plasma wake and a static longitudinal magnetic field. The corresponding length scales are very different in the two cases. In the regular LSW experiments, the laser wavelength plays a key role; however, in our approach the plasma wavelength is a fundamental ingredient. The plasma wavelength is approximately two orders of magnitude greater than the laser wavelength. Furthermore, the plasma wake is quasi-static; hence, a quasi-static pulse of ALPs is generated within the plasma. The parametric behaviour of the ALP flux is quite different to that produced by a laser beam propagating through a static magnetic field in the vacuum.

The results in Ref. [11] are based on analytical estimates of the ALP flux that emerge from a relativistic 1-dimensional electrostatic wave propagating through a constant longitudinal mag-

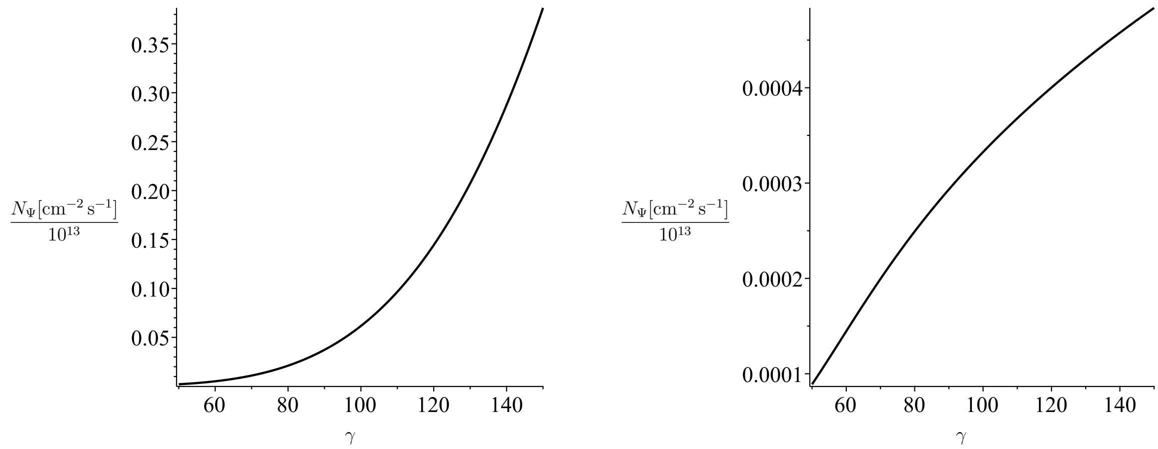

Figure 2: Estimates of the ALP flux density N_Ψ versus the Lorentz factor $\gamma \approx \omega_0/(\sqrt{3}\omega_p)$ of the wake in a 3-dimensional laser-wakefield accelerator, for the parameters $\omega_p = 2\pi \times 10^{13}\,\mathrm{rad\,s}^{-1}$, $B_s = 35\,\mathrm{T}$. The ALP mass is $10^{-5}\,\mathrm{eV}/c^2$ in the left-hand graph and $10^{-4}\,\mathrm{eV}/c^2$ in the right-hand graph. The ALP-photon coupling strength is $0.66 \times 10^{-10}\,\mathrm{GeV}^{-1}$ in both graphs.

netic field. Scaling arguments suggest that the ALP flux density produced in the 3-dimensional bubble, or blow-out, regime underpinning the laser-wakefield accelerator paradigm is $\sim 25\%$ of the ALP flux density in the 1-dimensional case [11].

Inspection of Fig. 2 shows that the ALP flux density is strongly dependent on the ratio ω_0/ω_p of the laser and plasma frequencies, and the details of its dependence are highly sensitive to the ALP mass. The parameters used in Fig. 2 have been chosen with respect to the regimes of interest to CAST [13] and ADMX [14]. The CAST collaboration have excluded ALP-photon coupling strengths that are greater than $\sim 0.66 \times 10^{-10}\,\mathrm{GeV}^{-1}$ if the ALP mass is less than $\sim 0.02\,\mathrm{eV}/c^2$, and the ADMX experiment is focussed on detecting ALPs of mass $\sim 10^{-5}\,\mathrm{eV}/c^2$. If the ALP mass is less than $\sim 1.8 \times 10^{-4}\,\mathrm{eV}/c^2$ then our results suggest that it may be possible to use a laser-wakefield accelerator to generate pulses of ALPs of tens of femtoseconds in duration, each of which has an individual flux comparable to the essentially continuous flux of solar ALPs at the Earth. One pulse of ALPs would be produced for each laser shot, and the plasma would need to be replenished between shots. However, it ought to be possible to produce a few pulses per second using the forthcoming ELI facilities [15]. Moreover, unlike the ALP flux from astrophysical sources, one can manipulate the ALP flux in our approach by adjusting the current through the solenoid and the laser-plasma parameters.

The reconversion of ALPs back to photons on the far side of the barrier could be facilitated using a similar dipole magnet ($\sim 9\,\mathrm{T}$) to that used by CAST. However, whilst x-ray photons predominate in the CAST experiments, the ALPs in our modified LSW configuration are expected to convert to terahertz photons. Single-photon detectors that operate in the terahertz region are important for applications in solid-state physics and astronomy [16] and, as such, considerable effort has been devoted to their development. Although the realisation of a modified LSW experiment of the type envisaged in Ref. [11] would be a considerable technical challenge, the results gained thus far suggest that further theoretical investigation is warranted.

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