No X-rays shining through a wall:

Searches for heavy, axion like particles with an X-Ray free electron laser

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Introduction

The axion was posed as a solution to the CP problem of QCD, but axion-like particles (ALPs) also arise in string theory and are a dark matter (DM) candidate. Most laboratory axion searches have concentrated on the 0.001-0.1 meV mass range however there is growing interest in heavier (DFSZ) axions above 10 meV which avoid the cosmological domain wall catastrophe [1]. Axions of such mass may also explain stellar energy losses beyond the ones accounted for by neutrino emission [2]. In this energy range, the most competitive bounds are from CAST [3], however the imposition of complimentary bounds from purely laboratory based searches is well motivated as these are less model dependent than searches which rely on astrophysically produced axions.

Here we describe a new laboratory search for axions at EuXFEL Hamburg, sensitive to a mass range including 1 meV-1 eV, which is largely unconstrained by laboratory experiments. X-Ray axion searches were previously performed at a 3rd generation synchrotron [4]; however limited flux prevented probing down to DM relevant couplings. Our work is a first step in developing a platform with improved sensitivity thanks to an increase in brightness by ~10^{10} at EuXFEL. Initial work has confirmed previous bounds on the coupling strength and probed a previously unexplored mass range. In future we hope to probe down to a coupling relevant to QCD axions in the keV mass range.

Experimental setup

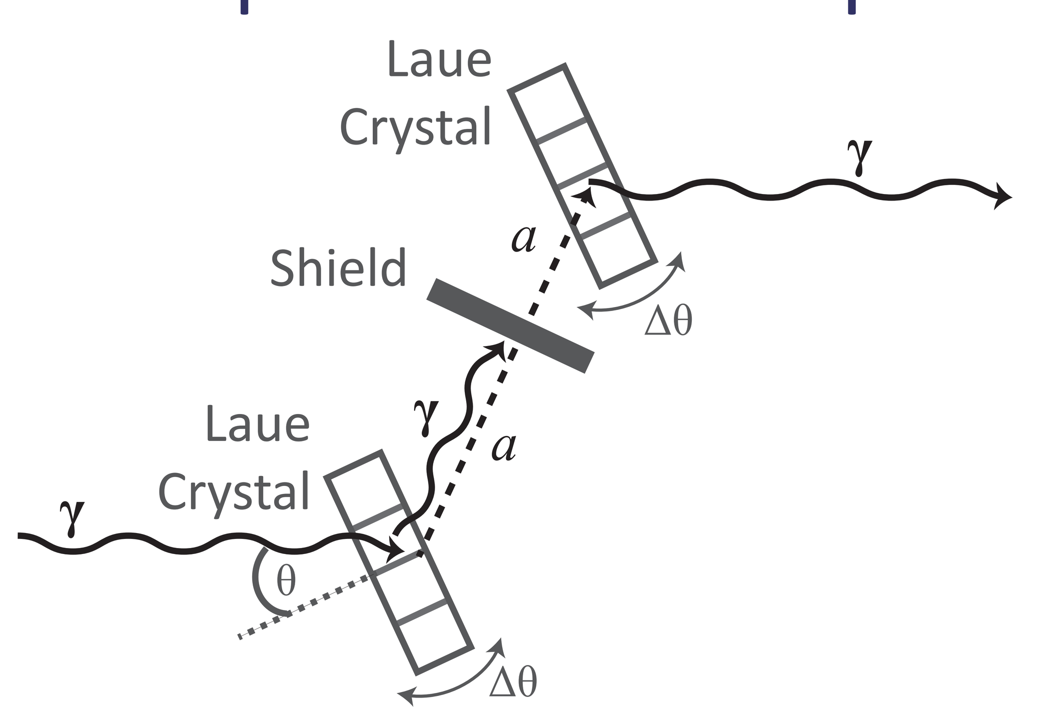

Figure 1: *The experimental setup employed in our experiment. Axion production and photon regeneration take place via the effective electric field within a pair of crystals (Germanium 220, Laue geometry).*

Our experiment exploits the Primakoff effect, via which axions / ALPs couple to electromagnetism through the Lagrangian

$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \boldsymbol{E}\,.\boldsymbol{B},$$

where $\boldsymbol{E}$ and $\boldsymbol{B}$ are the electric and magnetic fields; a is the axion field; and $g_{a\gamma\gamma}$ is the coupling constant.

The configuration we use to exploit this coupling is shown in figure 1. It consists of two Germanium (Ge) crystals oriented in the Laue geometry and parallel to one another. The s-polarised XFEL beam impinged from the right and so there was a parallel component between the B-field associated with the XFEL beam and the effective electric field of the crystal. As a result axions were predicted to be generated in the first crystal, and reconvert back into photons within the second crystal. Meanwhile, Bragg scattered photons were absorbed by the radiation shield. The effective electric field within the Ge has a strength ~ 10^{11} V/m which compares very favourably with the magnetic field strengths accessible using state-of-the-art electromagnets.

Reconverted photons were observed using a JUNGFRAU3 hybrid pixel detector [5]. The device was operated in a time-gated mode, with an acquisition time of 2 µs, centred on the X-Ray pulse trains. The XFEL was operated at 10 Hz, in a seeded mode, with a photon energy of 9.8 eV and one pulse per train.

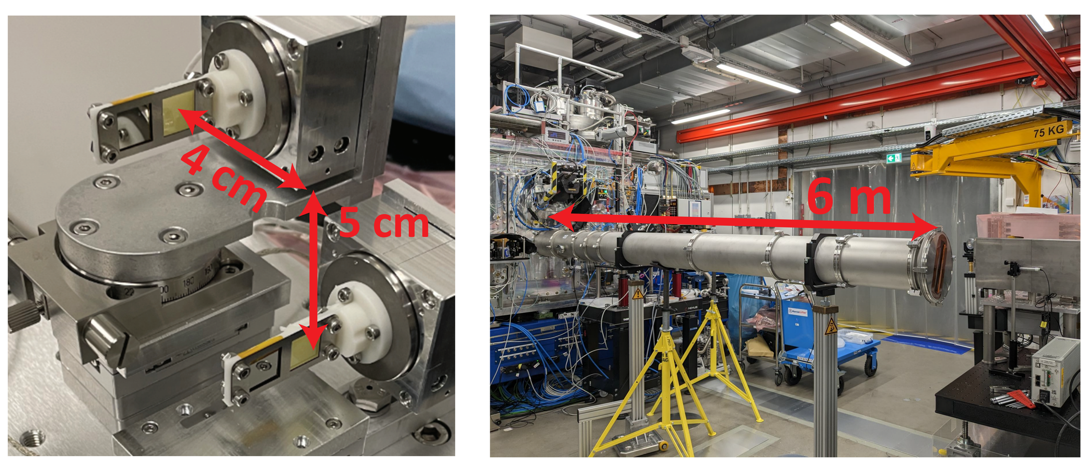

Figure 2: *(Left) Photograph showing the two Ge crystals, supported on a pair of piezoelectric rotation stages. (Right) Photograph of the HED instrument at EuXFEL. The detector was separated from the crystals by a 6 m evacuated flight tube to minimise the background.*

Mass sensitivity range

In figure 1, the angle between the wave-vector of the XFEL beam and the lattice planes of the crystal is denoted θ. It can be shown [6] that, when this angle is tuned to the Bragg-angle for the Germanium, the experiment is sensitive to the mass range which satisfies the inequality

$$|m_a^2 - m_\gamma^2| < \frac{4k_\gamma}{L},$$

where m_a is the axion mass; m_γ = 44 eV is the crystal's plasma frequency; k_γ = 9.8 eV is the photon energy; and L ~ 1 mm is the path length within the crystal.

When the crystals are detuned from the Bragg-angle by $\Delta\theta = \theta - \theta_B$, then the setup is instead sensitive to a narrow mass range, centred on

$$m_a = \sqrt{m_\gamma^2 + 2q_T k_\gamma \cos(\theta_B)\Delta\theta},$$

where q_T = 6.2 keV is the reciprocal lattice spacing. Therefore, by sweeping through Δθ, it is possible to search for a broad range of heavy axions with masses in the interval between the plasma frequency of the crystal and the projection of the incoming photon energy onto the reciprocal lattice vector.

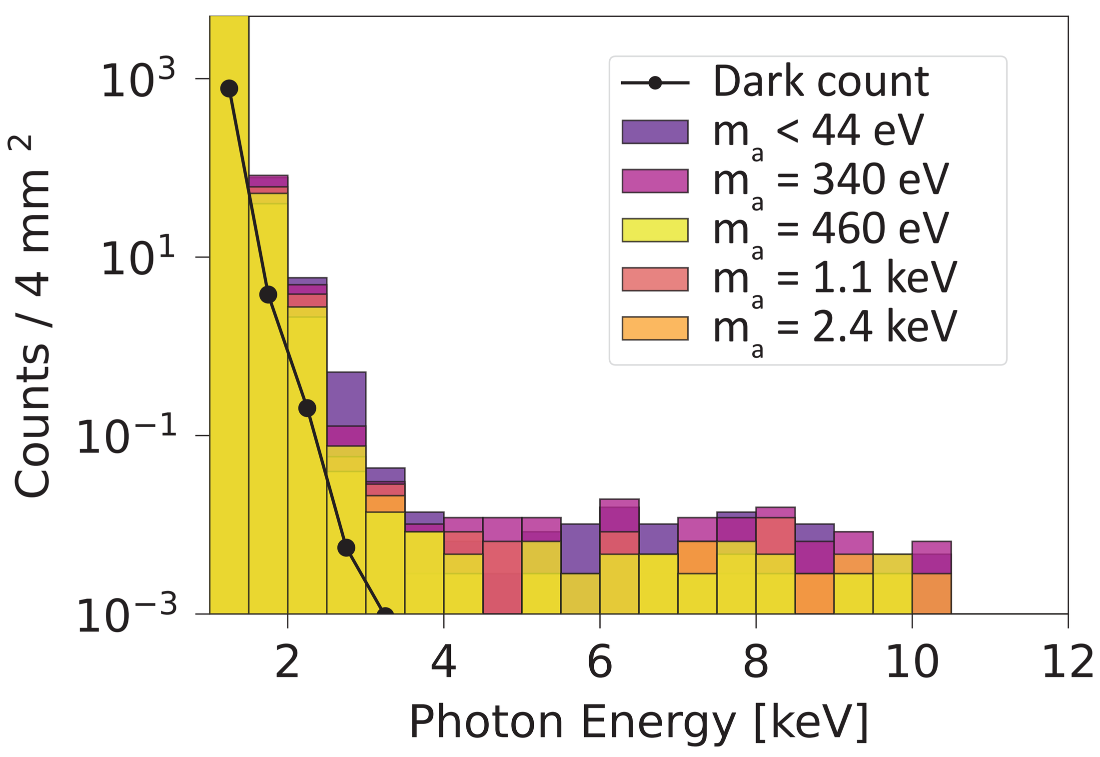

Figure 3: *Counts, summed across all acquisitions, scaled to the size of the X-ray spot on the detector plane, and compared with the scaled number of counts in a 24 hr dark run.*

Results

Figure 3 is a histogram which shows energy resolved events, summed across all data runs in the experimental campaign upon which we report. These are compared against the scales number of counts in a 24 hour long dark-run. Additionally, both sets of data are scaled to the area of the X-ray spot which was observed on the JUNGFRAU detector when the radiation shield was removed from the setup and both crystals were aligned to the Bragg angle. Any events which one might attribute to axion production are expected to fall within the region of this X-ray spot, and furthermore regenerated photons should have the same photon energy as the incoming XFEL beam (9.8 keV). The scaled number of counts in the range 9.5 – 10.5 keV is on the order of ~2%.

Figure 4 shows the transmission through the setup with the radiation shield removed (in blue), with the position of all 10 keV hits on the detector overlaid. In the figure there are no hits which overlap with the X-ray spot (darker blue region in the centre of the figure):

No events consistent with axion production were detected in any run.

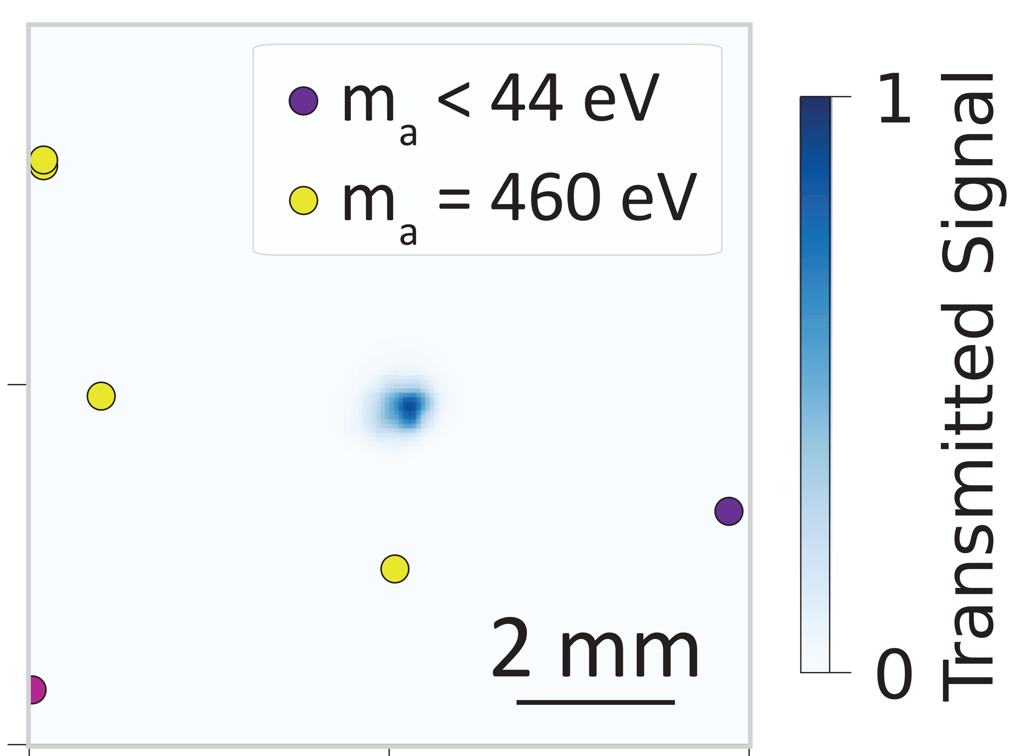

Figure 4: *An image showing the transmitted signal, obtained without the radiation shield, overlaid by the position of the 10 keV events across all data acquisitions.*

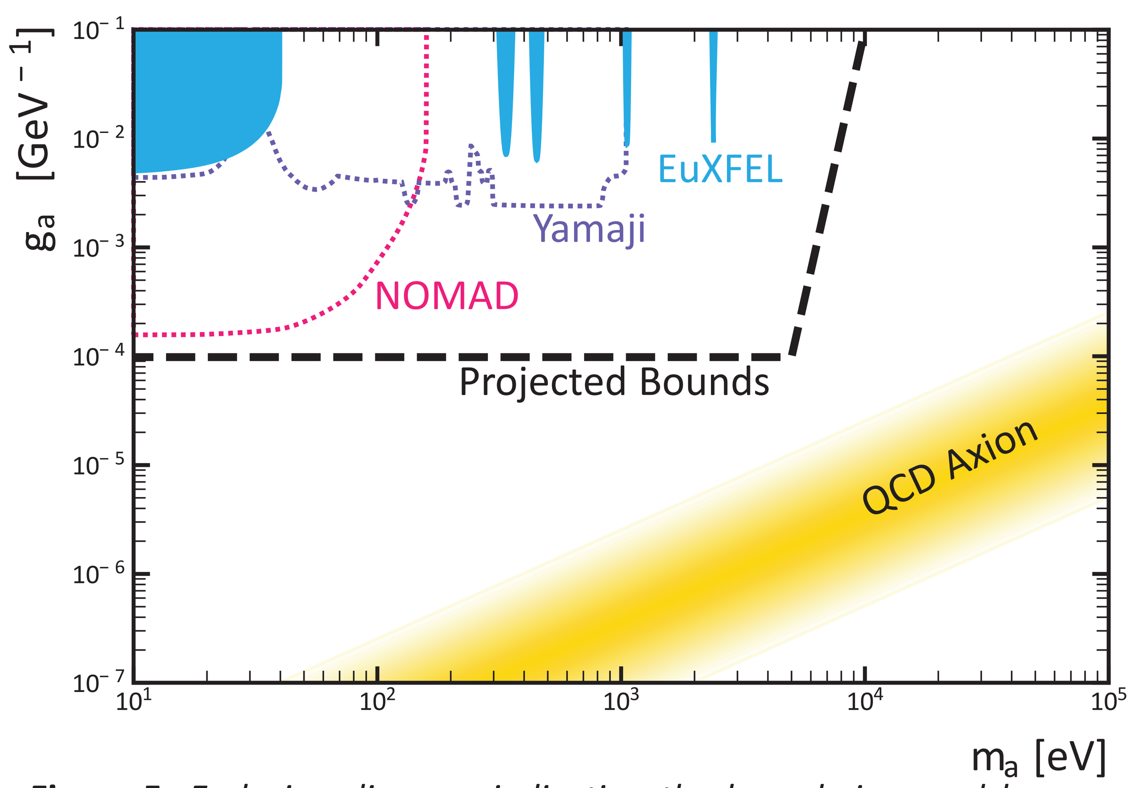

Figure 5: *Exclusion diagram indicating the bounds imposed by our initial experiment (red), compared with those from Yamaji et al. [4] (lilac), and those from NOMAD.*

Estimate of bounds

As described in [6], the bound on the coupling constant, for a value of Δθ, is given by

$$g_{a\gamma\gamma} < \frac{1}{E_{\text{eff}}\ \ L\ \ \cos\theta_B}\left(\frac{N_{\text{det}}}{\eta N_{\text{in}}}\right)^{1/4},$$

where N_{det} is the number of detected photons; N_{in} is total number of incident photons; and $\eta < 1$ is a factor accounting for the deviation from parallelism between the 2 crystals / the efficiency of the detection process.

The value of η was determined by removing the radiation shield and tuning the setup to the Bragg angle at the beginning of each data run. The ratio of X-ray dose on a passive upstream detector; to dose on the downstream detector was obtained in this characterisation phase. This ratio was used to obtain the number of input photons, from the data obtained using the upstream monitor, during acquisitions.

As shown in figure 6, the sensitivity of this search was on the same level as previous work on a 3rd generation synchrotron [4]. This is because the unattenuated flux from the XFEL heated the 1st crystal to the point where the setup became detuned in ~30 secs. To obtain a stable alignment the X-ray flux was attenuated by a factor of 10^{-3}. The XFEL was also operated in a seeded mode with 1 pulse per train.

Detection sensitivity limited by X-Ray heating.

Could be improved by a factor of 10^4.

Future prospects

Proposed changes for future experiments:

- Implement an active cooling scheme to mitigate the heat load on the Germanium
- XFEL enables an increase in X-Ray flux by a factor ~ 10^5
- Moving to a Bragg scattering geometry with HOPG (graphite) crystal will increase interaction length by factor ~ 50

Taken together these changes improve sensitivity by a factor of 10^4. The projected bounds in figure 4 show the expected sensitivity obtained by scaling our current result. The projected sensitivity is sufficient to probe a coupling relevant to QCD axions in the m_a ~ 10^3 eV mass range.

References

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