MADMAX: A Dielectric Haloscope Experiment

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Abstract. Axions emerge naturally from the Peccei-Quinn mechanism, which addresses the absence of CP violation in the strong interaction, and they can make up the cold dark matter (CDM) in the universe. If PQ symmetry was broken after inflation, the CDM axion mass would likely be in the range of \( \sim 26 \mu eV \) to \( \sim 1 \text{ meV} \), which is yet to be explored experimentally. We present a new dielectric haloscope experiment dedicated to the direct detection of QCD axion dark matter in the mass range of 40 to 400 \( \mu eV \) – the MAgnetized Disc and Mirror Axion eXperiment (MADMAX). Multiple dielectric discs and a mirror are placed in a strong magnetic field to utilize the axion-induced coherent electromagnetic wave emitted from each disc surface and the resonance effect therein, such that the axion-induced signal can be boosted to a level detectable by state-of-the-art low noise amplifiers. We will discuss the motivation, design and sensitivity of MADMAX; ongoing R&D studies and the project roadmap will also be presented.

1. Introduction

The axion arises from the Peccei-Quinn (PQ) mechanism \[1\], whereby a new global chiral U(1) symmetry is introduced, and is broken spontaneously at the PQ scale \( f_a \); the axion emerges as a pseudo Goldstone boson. Originally theorized to address the absence of CP violation in QCD, the axion also turns out to be an excellent CDM candidate \[2\]. The axion mass is given by \( m_a \simeq 5.7 \mu eV (10^{12} \text{ GeV}/f_a) \). The allowed \( m_a \) (or \( f_a \)) range which can produce the correct CDM abundance depends on the order of two critical cosmological events: the PQ symmetry breaking and inflation. In the case where the PQ symmetry breaking occurred before inflation, the vacuum realignment mechanism can provide the entire CDM in the form of cold axions for \( m_a \lesssim 0.5 \text{ meV} \), with the precise value determined by the initial misalignment angle at PQ symmetry breaking. If the PQ symmetry breaking happened after inflation, the prediction of \( m_a \) is much more difficult as the relic axion CDM density is not only given by the averaged vacuum realignment mechanism, but also affected by cosmic strings and domain walls associated with the patchy structure of the axion field. Nevertheless, currently the best estimate for the second scenario is a CDM axion mass of \( m_a \in (26 \mu eV, 1 \text{ meV}) \) \[3,4\].

There have been numerous experimental searches for the axion, notable among which are the haloscope experiments such as ADMX \[5\]. In haloscope experiments, the signal originated from axion-photon coupling is enhanced by a strong external magnetic field and traditionally by the coupling of the axion-induced electric field with a cavity. However, above 10 GHz (\( m_a \gtrsim 40 \mu eV \)), cavity haloscopes are increasingly difficult to build and operate. The dielectric haloscope presents a promising way to detect the axion-photon conversion for the \( m_a \) range of 40 to 400 \( \mu eV \), which gives rise to microwave photons in the range of 10 to 100 GHz. In this article, the concept behind dielectric haloscopes, and in particular MADMAX with its related R&D activities, will be discussed.
2. Dielectric haloscope

Consider a medium with dielectric constant $\epsilon$ and permeability $\mu = 1$ in a homogeneous static $B$-field $B_e$. The CDM axion field would induce a static oscillating electric field

$$E_a(t) = -\frac{\alpha}{2\pi\epsilon} C_{\alpha\gamma} B_e \theta(t),$$

(1)

where $\theta(t)$ is the axion field, $\alpha$ is the fine structure constant, and $C_{\alpha\gamma}$ is the model-dependent axion-photon coupling. Note that $E_a(t)$ is discontinuous at the boundary between two media with different $\epsilon$, which is not allowed by the axion-Maxwell equations. As a result, electromagnetic (EM) radiation is emitted at said boundary in the perpendicular directions such that the continuity condition is satisfied. In the case of a single metallic mirror with area $A$ placed in a vacuum with a magnetic field parallel to the mirror surface, the power emitted at the boundary is

$$P_0 = 2.2 \times 10^{-27} W \left( \frac{A}{1 \text{ m}^2} \right) \left( \frac{B_e}{10 \text{ T}} \right)^2 \left( \frac{\rho_a}{0.3 \text{ GeV/cm}^3} \right) C_{\alpha\gamma}^2,$$

(2)

where $\rho_a$ is the local galactic axion CDM density. When multiple dielectric discs are added parallel to the mirror, the EM emission at certain frequencies can be enhanced by the coherent emissions from all boundaries and their constructive interference within the discs and mirror:

$$P = P_0 \cdot \beta^2(\nu) = 1.1 \times 10^{-22} W \left( \frac{\beta^2(\nu)}{5 \times 10^4} \right) \left( \frac{A}{1 \text{ m}^2} \right) \left( \frac{B_e}{10 \text{ T}} \right)^2 \left( \frac{\rho_a}{0.3 \text{ GeV/cm}^3} \right) C_{\alpha\gamma}^2,$$

(3)

where $\beta^2(\nu)$ is called the power boost factor. Such a setup is dubbed a dielectric haloscope. It has been demonstrated theoretically that the frequency and bandwidth at which the axion signal is enhanced can be tuned by changing the disc spacings. The area under the $\beta^2(\nu)$ curve $\int d\nu \beta^2(\nu)$ is conserved, which means there is a tradeoff between the peak power and bandwidth; it also increases with the number of discs $N$. More details on the theoretical foundation of dielectric haloscope can be found in Refs. [6–8].

![Figure 1. Conceptual sketch of the MADMAX experiment.](image)

Based on the aforementioned dielectric haloscope concept, MADMAX proposes to use 80 LaAlO$_3$ ($\epsilon \approx 24$) discs, each with a diameter of 1.25 m. A sketch of the MADMAX experiment is shown in Fig. 1. The booster, focusing mirror and the antenna will be placed inside a 4K cryostat. The RF part of the low noise receiver (not shown) will be placed in a different cryostat behind the antenna. The 9 T magnetic field will be provided by a superconducting dipole magnet, which will be situated in a separate cryostat with a warm bore of 1.35 m in diameter to house the booster cryostat. The discovery potential of MADMAX for axion/axion-like particle (ALP) is shown in Fig. 2.
3. R&D activity highlights

3.1. Booster simulation

Simulations have been performed to factor in 3D effects including moding, disc tilting, surface roughness and antenna coupling loss [9]. The moding effect gives rise to a transverse momentum and results in an offset in the boost factor frequency compared to that of the 1D simulation. When the axion-induced emission is coupled to a Gaussian antenna with the same beam waist as that of the fundamental mode, 30% of the power cannot be received due to the fact that only the fundamental mode couples to said antenna at nearly 100% efficiency. In addition, disc tilting and surface roughness introduce mode mixing and lead to further loss. It is estimated that for the configuration shown in Fig. 1, the disc tilting should be limited to 0.1 milliradian, surface roughness < 10 µm, and dielectric loss tan δ < a few × 10⁻⁵.

Figure 3. The proof-of-principle booster. The focusing mirror and antenna are not pictured.

3.2. Proof-of-principle setup and measurements

Although the boost factor cannot be directly measured, it is strongly correlated with the EM response of the system and, therefore, can be inferred from the reflectivity measurement. A proof-of-principle setup has been built to study the EM response and mechanical stability of the system, as well as the development of a frequency tuning procedure. The booster of the setup is shown in Fig. 3 up to 20 sapphire (ε ≈ 9.4) discs with 20 cm diameter can be moved by the
precision motors. It has been demonstrated that the system has sufficient mechanical stability, and frequency tuning with up to five discs has been achieved.

3.3. Disc tiling
LaAlO$_3$ is currently chosen as the material for the discs for its large dielectric constant and small tan δ loss. However, single crystal LaAlO$_3$ can be grown with a maximum size of 3". A tiling technology has been developed, as shown in Fig.4, to glue small hexagon tiles with STYCAST® BLUE 2850FT to form a bigger disc. The effect that tiling has on the booster EM properties is under study. Meanwhile, investigations of alternative disc materials which can be fabricated in larger sizes are ongoing.

3.4. Receiver
A receiver chain, which consists of a cryogenic HEMT preamplifier and three heterodyne mixing receivers, has been built and tested. The HEMT preamplifier from Low Noise Factory has a ∼33 dB gain and ∼5 K noise temperature at 18-26 GHz when used in liquid helium. The IF signal at the end is recorded by four samplers with 50 MHz bandwidth connected in a daisy chain; the samplers have internal FPGAs that can perform real-time FFT and subsequent averaging. A “fake axion” signal with power of ∼1.2 × 10$^{-21}$ W at 18.4 GHz is injected into the receiver chain as a test, and it is detected with a 4.8σ significance after two days of measurement [10].

4. Project roadmap
A prototype detector which consists of 20 tiled LaAlO$_3$ discs with a 30 cm diameter will be built and commissioned at the University of Hamburg by December 2021; it will serve as a testbed for technical challenges such as the disc driving mechanics. Although the operations are nominally without magnetic field, tentative plans have been made to test the prototype inside the MORPURGO magnet at CERN which can produce a magnetic field of up to 1.6 T. Should the operations be successful, the first competitive limits for hidden photons and ALPs around $m_a$ ∼ 100 µeV will be set by the MADMAX prototype.

The 9 T magnet is the main cost and time driver of the experiment. The magnet feasibility study has been concluded with a positive assessment, and the academic and industrial partners have been appointed that will work towards the delivery of the dipole magnet to MADMAX in 2025. In the meantime, the operation of the prototype detector will continue, and the construction of the final booster will be carried out with the aim to start the commissioning of the full-scale detector in HERA Hall North, DESY, in 2025.

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