PROCEEDINGS OF SCIENCE

MADMAX – A Novel dielectric haloscope detector for post-inflationary axion dark matter searches

Anton Ivanov, [a]Chang Lee[a,*], Xiaoyue Li[†a], Olaf Reimann[a], and Derek Strom[a] for the MADMAX Collaboration

[a] *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany*

E-mail: changlee@mpp.mpg.edu

QCD Axions are leading dark matter candidates that additionally solve the strong CP problem. The latest lattice-QCD simulations strongly favor the 40–400 μeV mass range for the QCD axions generated after cosmic inflation. The MADMAX collaboration aims to detect the QCD axions in this mass range by converting them into traveling wave signals using a novel detector called a dielectric haloscope. We report the current progress of the MADMAX collaboration with a focus on a recent measurement using a scaled-down dielectric haloscope.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

[†] now at TRIUMF, 4004 Wesbrook Mall, Vancouver, BC V6T 2A3, Canada
[*] Speaker

PoS(ICHEP2022)109

1. Introduction

The identity of dark matter remains an open question in physics. Many extensions of the Standard Model postulate new symmetries that spontaneously break and yield light bosonic particles. These particles may form the local cold dark matter halo if their symmetry-breaking energy is large and their interaction with the standard model particles is feeble [1]. Among these light dark matter candidates, the QCD axions are best motivated because they simultaneously solve the strong CP problem [2–5]. The possible mass range of the QCD axion is vast, most strongly depending on the initial Peccei-Quinn symmetry-breaking angle θ. The dependence, however, is averaged out and becomes negligible if the PQ symmetry was broken after cosmic inflation. These *post-inflationary* production scenarios constrain the QCD axion mass much more tightly: The latest lattice-QCD simulations predict the *post-inflationary* QCD axions to be considerably heavier than previously thought, roughly around 100 μeV [6]. Fig. 1 summarizes the current state of the axion dark matter search. The MAgnetized disc and Mirror Axion eXperiment (MADMAX) collaboration aims to detect these *heavy* QCD axions using a novel detector concept called dielectric haloscope [7, 8].

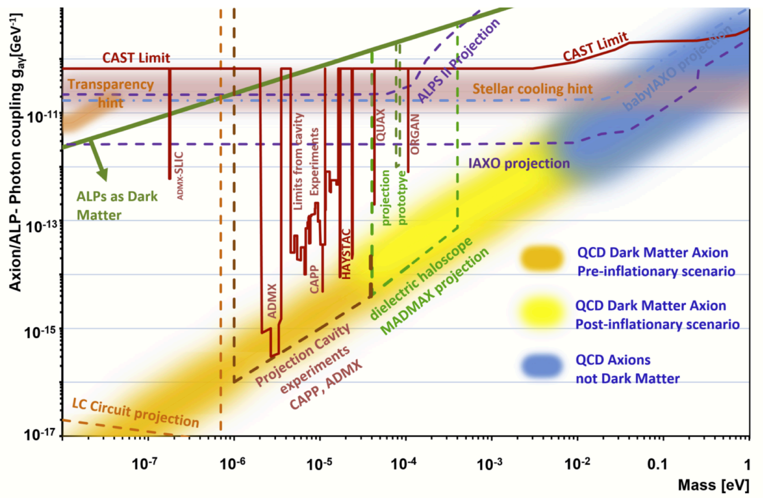

Figure 1: Axion dark matter search landscape in axion mass vs. its photon coupling strength. Projected sensitivities of the prototype and final MADMAX detector are shown. The final MADMAX detector is expected to be sensitive to QCD axion in the post-inflationary regime.

2. Detection principle

QCD axions and axion-like particles (ALPs) – extensions of the QCD axions that do not solve the strong CP problem – couple to two photons, such that

$$\mathcal{L}_{\text{int}} = g_{a\gamma}\boldsymbol{E} \cdot \boldsymbol{B}\theta. \tag{1}$$

Here, $\boldsymbol{E}$ and $\boldsymbol{B}$ are electric and magnetic fields, and $g_{a\gamma}$ is the axion-photon coupling strength. In laboratories, it is practical to provide a strong magnetic field B_e and measure the axion-induced electric field E^a that oscillates with the cold dark matter axion mass m_a. The amplitude of E^a is given by

$$E^a = -\frac{g_{a\gamma}B_e}{\varepsilon}a, \tag{2}$$

where a is the axion field θ multiplied by the PQ-symmetry breaking energy scale and ε is the electric permittivity of the medium. Because $g_{a\gamma}$ is very small, E^a is also very small beyond the

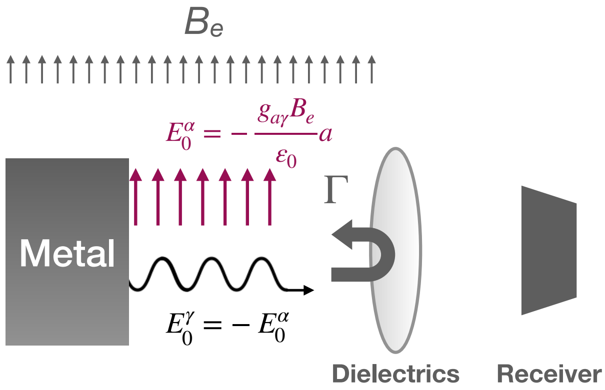

Figure 2: Scheme of a simple dielectric haloscope booster. The axion-induced oscillating electric field E_0^a induces a wave E_0^γ at the mirror interface. Dielectrics reflect a portion of E_0^γ boosting the energy stored in the vacuum and increasing the amount of power reaching the detector. Image from [12].

detection limit of the current technology. The unknown m_a makes the detection further complicated. A haloscope experiment needs to be able to enhance E^a for a wide range of m_a.

To probe the heavy QCD axion, dielectric haloscopes detect axion-induced traveling waves [9]. At media boundaries, the discontinuity of ε and E^a excites traveling waves. Such axion-induced traveling waves manifest as a mono-energetic peak above the background. The traveling wave signal power scales with B_e^2 and surface area but is independent of m_a. In the limit case of a perfect mirror, the emitted wave E^γ cancels out E^a at the mirror's surface: $E_0^\gamma = -E_0^a$. For QCD axions at $B_e = 10\,\mathrm{T}$, E^γ is $\sim 10^{-27}\ \mathrm{W/m^2}$, still far below the sensitivity of state-of-the-art detectors. To significantly boost the emitted power, a dielectric haloscope i) coherently sums the traveling wave signal from multiple boundaries and ii) relies on reflection from the dielectric surfaces. Reconfiguring the dielectric spacings will enable boosting and scanning a broader m_a range. The dielectric haloscope concept can be scaled up to be sensitive to QCD axions with current detector technology [7].

Fig. 2 illustrates how a minimal dielectric haloscope boosts the axion-induced signal power. E_0^γ emitted from the mirror reflects from the dielectric surface by reflectivity Γ. As the reflected wave is incident on the mirror surface, the axion-induced emission from the mirror needs to compensate for it further. In turn, these multiple reflections boost the stored energy between the mirror and the dielectric. The amount of power leaking to the detector depends on $|\Gamma|$, where in the mirror limit case of $|\Gamma| \to 1$, the system behaves like a cavity, and no power arrives at the detector. Multiple layers of dielectrics will increase $|\Gamma|$, transform the receiver impedance [10], and increase the signal power arriving at the receiver. In the case of systems with more discs, the E^γ emission from each dielectric surface needs to be considered [11], and the system will be less resonant. The receiver, a horn antenna or tapered waveguides, is designed to match the desired axion signal and suppress unwanted parasitic modes.

3. Closed booster and ALP search

To experimentally verify the dielectric haloscope concept, we built a small proof-of-principle detector illustrated in Fig. 3, named CB-100. A copper mirror and three 100-mm diameter, 1-mm thick sapphire discs ($\varepsilon_r \approx 9.3$) form the dielectric haloscope. Aluminum separation rings secure the disc spacings, which are chosen to transform the TE_{11} mode impedance of the mirror closer

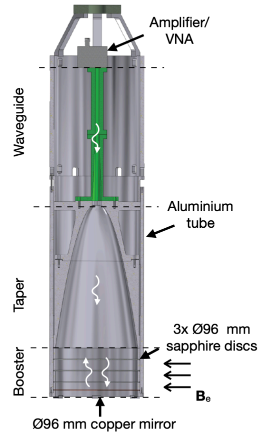

Figure 3: Schematic of the closed dielectric haloscope, tapered waveguide, and the waveguide transition.

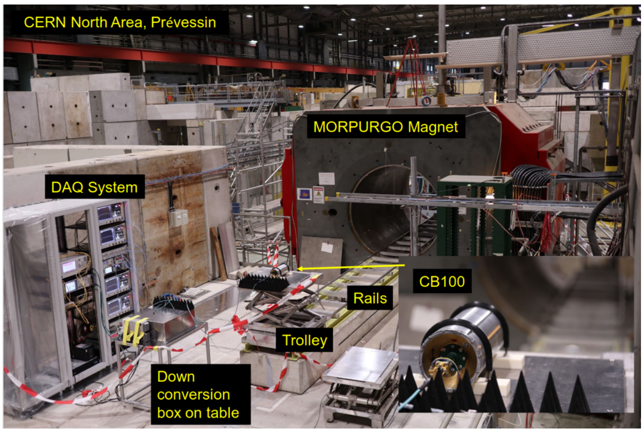

Figure 4: The measurement setup in Morpurgo with CB-100.

to the TE_{11} mode impedance of the waveguide and maximize the axion-induced emission near 19 GHz. The rings also form a conductive boundary that transmits only cylindrical waveguide modes. Such a *closed boundary* significantly simplifies the system understanding and analysis. A parabolic tapered waveguide focuses the signal power and delivers it to the receiver. E^a mainly excites the fundamental transverse electric mode, i.e., TE_{11} mode with an efficiency of about 0.7.

A room-temperature reflectivity measurement confirms that the peak at 18.77 GHz corresponds to the intended axion-signal boost mode. While the measured group delay agrees well with the simulation, the measured loss is higher than expected. The dominant source of the loss was the strong surface currents at the contact of the disc with the metal wall. Gold layers sputtered on the discs' rim reduce the loss to -1 dB. Most other peaks originate from unwanted mode conversion in the tapered waveguide; however, they are sufficiently separated from the main peak. By comparing the measured thermal noise with the detector model, we claim that CB-100 boosts the axion signal by $\sim$ 700 at its main boost peak.

The MADMAX Collaboration identified 1.6-T Morpugo dipole magnet at CERN [13] as a suitable site for testing various stages of the dielectric haloscope concepts, including CB-100 [14]. CERN agreed on MADMAX using Morpurgo during test beam shutdown periods. Morpurgo provides a homogeneous 1.6-T magnetic field inside a 1.6-m-diameter open, warm bore, large enough to accommodate a cryogenic vessel containing the MADMAX prototype.

All measurement equipment, including the receiver system and CB-100, were transported from Munich to CERN and installed in the Morpurgo area, as shown in Fig. 4. Electromagnetic interference and fringe magnetic field in the Morpurgo area had negligible impacts on our measurement. The first ALPs data were recorded for a dielectric haloscope in a 1.6-T field between April 7-8, 2022, for a total of 10 hours. Analysis of these data is ongoing. Fig. 5 shows the projected sensitivity. The minimum $g_{a\gamma}$ is about 10^{-10} GeV^{-1} near 78.6 μeV, comparable to the exclusion limit from the

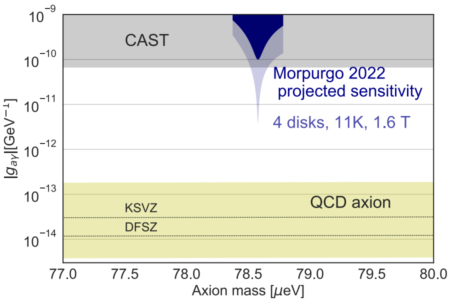

Figure 5: Projected sensitivity of CB-100 ALP search at the Morpurgo magnet

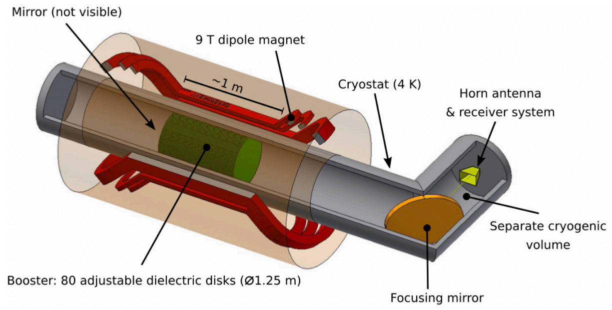

Figure 6: Schematic of the final MADMAX detector.

CAST experiment [15]. We plan an upgraded search with a cryogenic temperature and a longer measurement time.

4. Current status of the MADMAX experiment

The final goal of the MADMAX collaboration is to realize the optimized dielectric haloscope and search for QCD axion dark matter in the 40–400 μeV mass range [7, 8]. In Fig. 6, we report a schematic of the experiment in its most ambitious form. It consists of up to 80 1-m^2 dielectric discs at cryogenic temperature. The discs are reconfigurable via piezo positioners, allowing the detector to cover a broad axion mass range. CEA Saclay and Bilfinger Noell are designing a 9-T dipole magnet, inside which the detector will operate. A quench study of the coil conductor, NbTi superconductor inside a copper jacket, is ongoing. The final MADMAX experiment will be hosted in the north hall of the HERA experiment at DESY, with expected commissioning in 2028.

The MADMAX collaboration foresees many technical challenges related to the design, construction, and operation of a complicated microwave system inside a strong magnetic field and cryogenic environment. To demonstrate feasibility, the collaboration tested a custom piezo positioner at the cryogenic temperature inside a 5-T field of an ALP II magnet [16]. The positioner operated successfully. Project-200, a scaled-down dielectric haloscope with 200-mm discs, successfully cooled down and operated at CERN's Cryolab and inside the Morpurgo magnet. The collaboration also explores the use of low-noise quantum amplifiers, such as traveling wave parametric amplifiers [17]. The prototype cryostat is currently being funded by the German Research Foundation, and it will be installed in the low-radiation laboratory at the University of Hamburg. In the long term, we plan to use the prototype inside CERN's Morpurgo magnet for a dedicated ALP search. Fig. 1 reports the projected sensitivity of the final MADMAX detector.

References

[1] Jaeckel J and Ringwald A 2010 *Annual Review of Nuclear and Particle Science* **60** 405–437 URL https://doi.org/10.1146/annurev.nucl.012809.104433

[2] Peccei R D and Quinn H R 1977 *Phys. Rev. Lett.* **38**(25) 1440–1443 URL https://link.aps.org/doi/10.1103/PhysRevLett.38.1440

[3] Peccei R D and Quinn H R 1977 *Phys. Rev. D* **16**(6) 1791–1797 URL https://link.aps.org/doi/10.1103/PhysRevD.16.1791

[4] Weinberg S 1978 *Phys. Rev. Lett.* **40**(4) 223–226 URL https://link.aps.org/doi/10.1103/PhysRevLett.40.223

[5] Wilczek F 1978 *Phys. Rev. Lett.* **40**(5) 279–282 URL https://link.aps.org/doi/10.1103/PhysRevLett.40.279

[6] Borsanyi S *et al.* 2016 *Nature* **539** 69–71 URL https://doi.org/10.1038/nature20115

[7] Caldwell A *et al.* (MADMAX Working Group) 2017 *Phys. Rev. Lett.* **118**(9) 091801 URL https://link.aps.org/doi/10.1103/PhysRevLett.118.091801

[8] Brun P *et al.* (MADMAX Collaboration) 2019 *The European Physical Journal C* **79** 186 URL https://doi.org/10.1140/epjc/s10052-019-6683-x

[9] Horns D *et al.* 2013 *Journal of Cosmology and Astroparticle Physics* **2013** 016 URL https://dx.doi.org/10.1088/1475-7516/2013/04/016

[10] 2007 Smith chart calculations *The ARRL Antenna Book 21st edition* ed Straw R D (Newington: ARRL) chap 28

[11] Millar A J, Redondo J and Steffen F D 2017 *Journal of Cosmology and Astroparticle Physics* **2017** 006–006 URL https://doi.org/10.1088/1475-7516/2017/10/006

[12] Lee C *et al.* 2021 *Journal of Physics: Conference Series* **2156** 012041 URL https://dx.doi.org/10.1088/1742-6596/2156/1/012041

[13] Morpurgo M 1979 *Cryogenics* **19** 411–414 ISSN 0011-2275 URL https://www.sciencedirect.com/science/article/pii/0011227579901267

[14] Majorovits B and Pralavorio P (MADMAX) 2021 Usage of the CERN MORPURGO magnet for the MADMAX prototype Tech. rep. CERN Geneva URL https://cds.cern.ch/record/2773067

[15] Anastassopoulos V *et al.* 2017 *Nature Physics* **13** 584–590 ISSN 1745-2481 URL https://doi.org/10.1038/nphys4109

[16] Albrecht C *et al.* 2021 *EPJ Techniques and Instrumentation* **8** 5 ISSN 2195-7045 URL https://doi.org/10.1140/epjti/s40485-020-00060-5

[17] Ranadive A *et al.* 2022 *Nature Communications* **13** 1737 ISSN 2041-1723 URL https://doi.org/10.1038/s41467-022-29375-5