MADMAX: A new Dark Matter Axion Search using a dielectric Haloscope

Béla Majorovits[1] *and Javier Redondo*[2] *for the MADMAX working group*
(A. Caldwell[1]*, G. Dvali*[1,3]*, C. Gooch*[1]*, A. Hambarzumjan*[1]*, B. Majorovits*[1]*, A. Millar*[1]*, G. Raffelt*[1]*, J. Redondo*[2]*, O. Reimann*[1]*, F. Simon*[1]*, F. Steffen*[1]*)*

[1]Max-Planck-Institut für Physik, München, Germany,
[2]University of Zaragoza, Spain,
[3]Ludwig Maximilians Universität München, Germany,

DOI: http://dx.doi.org/10.3204/DESY-PROC-2016-03/Majorovits_Bela

Axions are an intriguing dark matter candidate, emerging from the Peccei-Quinn solution to the strong CP problem. Current experimental searches for axion dark matter focus on axion masses below 40μeV. However, if the Peccei-Quinn symmetry is restored after inflation the axion mass is predicted to be in the 100 μeV range. A new project based on axion-photon conversion at the transition between different dielectric media is presented. The axion-photon conversion could be enhanced by a factor $\sim 10^5$ over a single mirror by using $\sim$ 80 layers of dielectrics. Within a 10 T magnetic field this could be enough to detect $\sim$ 100 μeV axions with HEMT linear amplifiers. The proposed design for an experiment is discussed. Results from noise, transmissivity and reflectivity measurements in a prototype setup are presented. The expected sensitivity is shown.

1 Introduction

Axions are hypothetical low-mass bosons which emerge as a consequence of the Peccei-Quinn mechanism that explains the absence of CP-violating effects in quantum chromodynamics. They provide an attractive candidate for cold dark matter. There are two general scenarios for dark matter axions: either the Peccei-Quinn symmetry is restored after inflation, or remains unbroken. In the latter scenario, axion dark matter is produced through the misalignment mechanism, which can be arrange to have the correct relic density for a wide range of axions masses by varying the initial conditions with values $\sim$ 10 μeV considered most natural. In the first scenario the observable universe contains many casually disconnected patches with different initial conditions which must be averaged over to give the relic abundance. Additionally cold dark matter axions are produced by the decay of axion strings and domain walls leading to a higher favoured mass range $m_a \sim 100$ μeV for dark-matter axions [1].

Most experimental efforts for detecting dark-matter axions, notably the ADMX and ADMX-HF experiments [2, 3], focus on axion masses below $\sim$ 40 μeV. These experiments take advantage of the resonant enhancement of a cavity to boost the axion-photon conversion in a magnetic field and so gain sensitivity to axion dark matter. This technique is most effective for $\mathcal{O}(10)$ μeV axions: using cavities to search for axions in the 100 μeV range is extremely technically challenging. Alternative methods more suited to search for high mass axions are needed.

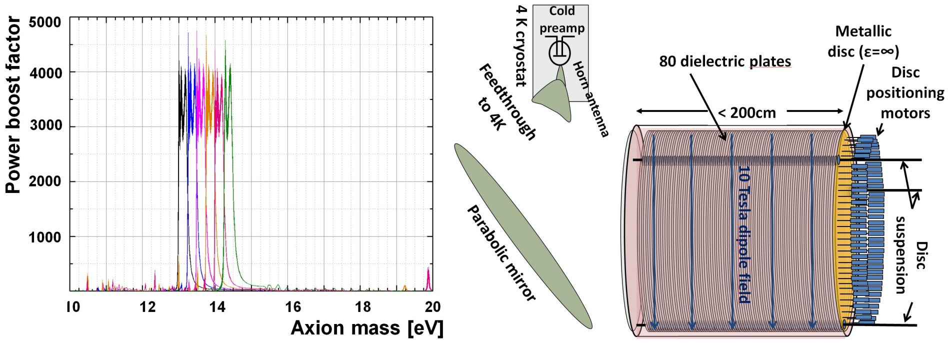

Figure 1: Left: EM simulations of boost factor in dielectric booster with 20 $LaAlO_3$ discs. Right: Conceptual idea for a haloscope that could scan for axions with masses around 100μeV.

2 Dielectric haloscope concept and experimental idea

To scan the axion mass range above 40 μeV, we exploit a novel dielectric haloscope approach derived from the concepts described in [4, 5]. The expected radiation power density from axion-photon conversion at a transition between materials with different dielectric constant ϵ in a magnetic field is

$$P/A = 2 \times 10^{-27}\ \mathrm{W/m^2}\ (B_{||}/10\,\mathrm{T})^2\, c_\gamma^2\, F(\Delta_{\epsilon_1,\epsilon_2}), \tag{1}$$

where A is the surface area, $B_{||}$ the magnetic field parallel to the surfaces, $C_{a\gamma}$ the axion-photon coupling constant normalized to $\alpha/(2\pi f_a)$ [6], and $F(\Delta_{\epsilon_1,\epsilon_2})$ is a function depending on the dielectric constants of the two media. For a metallic mirror in vacuum $F(\Delta_{0,\infty}) = 1$. In order to obtain a detectable power of $P \sim 10^{-23}W$ a mirror magnetized to 10 T field parallel to its surface with $A \sim 5000$ m^2 would be needed, unachievable with current technology.

Instead we propose building a dielectric haloscope: a series of high-ϵ material discs placed in front of a metallic mirror of the same area, contained in a magnetic field. Unlike a resonator, this device is open on one side. By adjusting the spacing between the discs, constructive interference can lead to a boost of the expected axion field induced EM power over a sizeable bandwidth. The power boost factor is defined as the power generated in the booster normalized to the power generated by a single metallic surface with same area. It is a function of the frequency, the number and spacings between the discs, and the dielectric constants of the chosen materials.

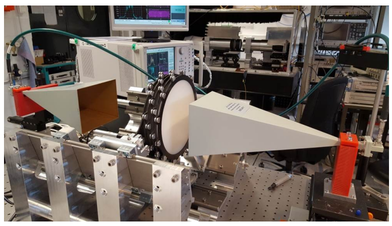

Figure 2: Preliminary prototype setup for transmissivity measurements with four adjustable Al_2O_3 discs.

The axion field acts as a current in Maxwell's equations, which can be treated classically. The power boost factor as a function of frequency from a first simulation is shown in Fig. 1, left. This used a setup consisting of 20 discs made from $LaAlO_3$ ($\epsilon \sim 24$) and achieves a power boost factor $\gtrsim 3{\cdot}10^3$ within a bandwidth of 250 MHz. The frequency range in which the boost is obtained can be varied by changing the displacement between the discs.

Further investigations using EM modelling have shown that, the area under the power boost factor vs frequency curve scales linearly with the number of discs in the booster. Using this relation it seems feasible that a setup consisting of ~80 discs made from $LaAlO_3$ can have a boost factor of $\sim 10^5$ in a 40 MHz wide frequency range. Using discs with a diameter of 1 m and a 10 T dipole field, a total power of $\sim 10^{-23}$ W could be generated by high mass dark matter axions. A sketch of the proposed MADMAX setup is shown in Fig. 1, right.

While this is a mechanically challenging setup, it has the advantage of flexibility. One can adopt a significantly broadband search strategy, probing a large frequency range within a reasonable measurement time and, in the event that the broad bandwidth search leads to evidence for a signal, the haloscope can be tuned to higher boost factor across a narrow bandwidth. This would enhance the signal to noise ratio, allowing speedy confirmation of a detection.

One of the big challenges in the experiment will be the availability of a $\sim$ 10 T dipole magnet that allows to house $\sim$ 1 m diameter discs with a length up to 2 m. Presently two design concepts are under discussion, the canted cosine theta [8] and the racetrack [9] designs. Initial investigations indicate that both design concepts are suitable to reach the design criteria. In the near future we will see which of these is better suited for the current experimental proposal.

3 First measurements and sensitivity projection

To determine the required signal strength, a radiometer based on heterodyne detection using a HEMT preamplifier [7] has been built. It was used for a first measurement of a weak signal at 20 GHz with 3×10^{-21} W at room temperature. The fake signal was detected within one week measurement time with $6\,\sigma$ separation from background. According to the data sheet, operating the preamplifier at 4 K temperature reduces its noise by another two orders of magnitude, hence, allowing for the detection of signals with power of the order of 3×10^{-23} W, if the noise contribution of the haloscope itself is low enough.

As transmissivity and reflectivity of the haloscope are correlated with the boost factor curve they can be used to verify the simulated boost factor behaviour. We use this to both test our calculations of the boost factor, and to potentially aid correct disc placement.

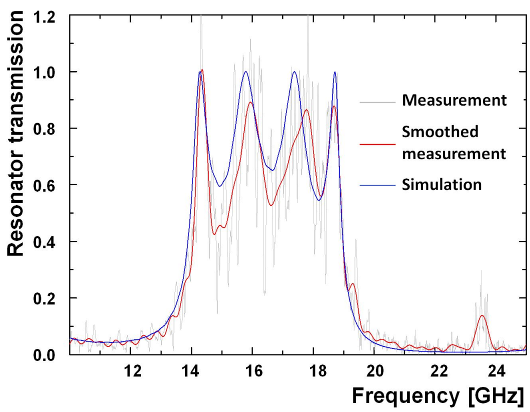

Figure 3: First transmission measurement (gray) taken with five Al_2O_3 discs between receiver and emitter. The smoothed measurement curve (red) can be compared to the behavior predicted by simulation (blue).

This has been done in the prototype setup shown in Fig. 2 where five sapphire (Al_2O_3 with $\epsilon \sim 10$) discs with 200 mm diameter each are used. Discs are positioned by precision motors with a precision of roughly 15 μm. The unceratinty on positioning is due to the mechanical setup. Comparison of transmissivity measurement with simulation is shown in Fig. 3. While details of the transmissivity behaviour slightly differ, encouragingly the general behaviour is similar, especially the position of the peak at highest frequencies. The same has been verified for reflectivity measurements using group delay peaks.

A long term reflectivity measurement using four saphire discs and a metallic mirror was performed to monitor the stability of the group delay peak. The variations of the peak position, attributed to mechanical (vibration) or thermal (contraction or expansion) changes in the setup, are of the order of 1 MHz, and so substantially narrower than the envisioned bandwidth of the boost factor. Even under these experimental conditions without vibrational damping and precise climate control long term measurements can be performed over a sizeable bandwidth.

To estimate the sensitivity of the proposed experiment, we assume a setup consisting of 80 discs with 1 m^2 surface area each, achieving a boost factor of $\gtrsim 10^4$ with a bandwidth of 50 MHz, and cryogenic preamp with a noise level of 8 K. Inside a 10 T dipole magnetic field this would allow for scanning the interesting dark matter QCD axion parameter space, assuming purely axionic dark matter. Each measurement would take approximately one week. The projected sensitivity is depicted in Fig. 4.

4 Outlook and Conclusions

Axions are amongst the best motivated dark matter candidates, with interesting and unique phenomenology. However, the high mass (40–200 μeV) axions predicted for scenarios in which Peccei-Quinn symmetry breaking occurs after inflation are beyond the reach of current experiments. A novel approach to study high mass axions is a dielectric haloscope, using a series of dielectrics contained in a parallel magnetic field to enhance the conversion of axions-to-photons. A comparison of simulations with first measurements indicate that this approach could scan the interesting dark matter QCD axion mass range within a reasonable time span.

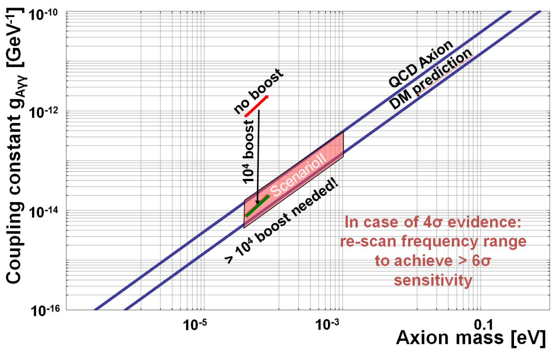

Figure 4: Projected MADMAX sensitivity

Acknowledgments: The prototype setup used for first measurements was partly funded as a seed project by the DFG Excellence Cluster Universe.

References

[1] T. Hiramatsu *et al.*, Phys. Rev. D **85**, 105020, (2012), Erratum ibid. **86**, 089902, (2012) ; M. Kawasaki *et al.* Phys. Rev. D **91**, 065014 (2015)

[2] G. Rybka, Proceedings of the 13th Int. Conf. on Topics in Astroparticle and Underground Physics (TAUP 2013) Phys. Dark Univ., **4**, 14 (2014)

[3] B. M. Brubaker *et al.*, arXiv:1610.02580.

[4] D. Horns *et al.*, JCAP **1304**, 016, (2013) [arXiv:1212.2970].

[5] J. Jaeckel and J. Redondo, Phys. Rev. D **88**, 115002 (2013) [arXiv:1308.1103].

[6] A. Ringwald *et al.*, in C. Patrignani et al. (Particle Data Group), Chin. Phys. C **40**, 100001 (2016)

[7] Low Noise Factory, datasheet for LNF-LNC6R_20A, www.lownoisefactory.com, site visited: Oct. 11. 2016

[8] S. Caspi et al., IEEE Trans. Appl. Supercond. **24**, 4000404 (2014)

[9] E. Rochepault, P. Vedrine and F. Bouillault, IEEE Trans. Appl. Supercond. **22**,4900804 (2012)