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The MADMAX collaboration:

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Abstract

The MADMAX collaboration proposes to search for QCD dark matter axion in the range 40-400 µeV using the novel dielectric haloscope concept. In order to validate this technique a prototype will be built and needs to be tested in a large bore dipole magnet. The CERN Morpurgo magnet, currently available in EHN1 and operated by ATLAS for its test beam on the H8 line, could be used for that purpose. The period of interest will be during the SPS shutdowns in the period 2022-2025. In addition to the prototype validation, one month of operation in the MORPURGO magnet will allow to probe an unexplored region of the ALP and dark photon parameter spaces.
1 Executive summary

After decades of investigation, the QCD Dark Matter axion search is approaching a crucial period where theory predictions will be tested against the experimental data. The MAgnetized Disc and Mirror Axion eXperiment (MADMAX) collaboration is aiming to search for dark matter axions by using the unique dielectric haloscope concept. The dielectric haloscope is presently the only concept with which it seems realistic to reach a sensitivity to scan the very well motivated axion mass range between 40 and 400 $\mu$eV. This mass range covers the predictions of the post-inflationary Peccei Quinn symmetry breaking scenario and masses compatible with the range $\pi > |\theta_i| > 2.4$ in the pre-inflationary Peccei Quinn symmetry breaking scenario.

As a first step towards realization of the experiment it is planned to build a down-scaled prototype in order to verify the technological feasibility and potentially to perform first searches for ALPs in an unexplored parameter space.

The MADMAX collaboration investigates the possibility to use the MORPURGO magnet at CERN [1] located in EHN1 on the H8 beam line for its MADMAX prototype. It would allow to test and verify the mechanical behavior of a prototype booster inside a strong magnetic field and to potentially obtain first results in a search for Dark Matter ALPs. This could be done during the SPS shutdown periods in 2022-2025. In this document we describe the motivation for MADMAX, the design idea and the scope of the prototype and we outline the measurements foreseen inside the MORPURGO magnet. Also requirements to the site where the prototype could be operated are described. Tentative time lines for usage of the prototype booster inside the MORPURGO magnet are given.

2 MADMAX for the search of Dark Matter Axions

Axions arise from the possibly most elegant solution to the strong CP problem via Peccei Quinn symmetry breaking [2], [3]. If indeed this mechanism leads to the non-observation of the complex CP violating phase $\theta$ in the QCD Lagrangian, axions inevitably also must constitute, at least partly, to dark matter [4].

The coupling of axions to photons is suppressed by $f_a$: $g_{a\gamma\gamma} \propto f_a^{-1}$. Due to this coupling, for $f_a \lesssim 10^8$ GeV, corresponding to axion masses above $\gtrsim 10^{-2}$ eV stellar cooling efficiencies higher than observed would be expected [5].

Also, the axion mass is related to the Peccei-Quinn symmetry breaking scale via $m_a \propto f_a^{-1}$. Therefore, the contribution of axions to dark matter, or vice versa a prediction on the axion mass based on the observed dark matter density depends on the energy scale of Peccei-Quinn symmetry breaking $f_a$.

There are two scenarios leading to different boundary conditions for preferred axion masse ranges: In the case of $f_a$ being higher than the inflationary energy scale the nowadays observable universe would consist of a single patch that was in causal contact during Peccei-Quinn symmetry breaking, hence the intial random phase $\theta_i$ would have been the same everywhere. The axion mass would then naively be expected to be in the range between
1 neV for $|\theta_i| = 0.01$ and $\approx 0.3$ meV for $|\theta_i| = \pi$. Very low masses $\lesssim 1$ neV are rather unlikely, as these would require unnaturally small $|\theta_i| \lesssim 0.01$ angles after Peccei-Quinn symmetry breaking. This gives the preferred range $1$ neV $\lesssim m_a \lesssim 10$ meV. In the scenario in which Peccei-Quinn symmetry breaking occurred after the inflationary phase, today’s observable and causally connected universe would consist of many patches that were not in causal contact during Peccei-Quinn symmetry breaking. Thus the overall mass bound in axions can be estimated. This leads - for the assumption that all Dark Matter is made up by axions - to an expected mass range for axions of tens to few hundreds $\mu$eV.

The preferred mass ranges for Dark Matter axions are shown in Fig. 1 as orange and

![Figure 1: Axion to photon coupling constant vs. axion mass. The broad line shows the expected mass range for axions if they solve the dark matter problem. Cavity searches like ADMX [13], CULTASK [14] and HAYSTAC [15] are sensitive to dark matter axions for masses between $\approx 1$ and $40 \mu$eV. MADMAX will be sensitive to dark matter axions in the mass ranges between 40 and 400 $\mu$eV. The MADMAX prototype could be sensitive to uncovered ALP parameter space in the mass window indicated, assuming few months of operation in the MORPURGO magnet. Also the parameter ranges for ALPs consistent with astrophysical observations are indicated. In addition existing exclusion limits from CAST [16] as well as the projected sensitivities of ALPS II [17] and IAXO [18] (independent of the dark matter hypothesis) are shown.](image-url)
Figure 2: Sketch of the basic design idea of the final MadMAX experiment. The booster, consisting of $\approx 80$ LaAlO$_3$ disks with 1.25 m diameter positioned in front of a dielectric mirror is contained inside a cryostat together with the beam optics consisting of a focusing mirror and a horn antenna to collect the signal. The cryostat is placed inside the aperture of a 9.2 T dipole magnet. The signal detector is contained in a separate cryogenic volume.

yellow bands for the pre- and post-inflationary scenarios, respectively.

Independently from the QCD axion, any theory containing spontaneously broken U(1) symmetries that is explicitly broken introduces axion like particles (ALPs). String theory, for example, predicts many such candidates, colloquially sometimes also called the ”axiverse” [6]. For these there are no obvious correlations between the symmetry breaking scale and the mass. Also these ALPs could explain the Dark Matter problem.

In recent years astrophysical observations have shown deviations from expectations that could be explained by such ALPs: notably, some pulsating white dwarfs have been found that exhibit a faster than explainable decrease of their rotation frequency. Additionally there seems to be too few horizontal branch stars in some globular clusters. These observations could be explained by ALPs cooling with a relevant coupling constant $g_{\text{ALP}\gamma\gamma} \approx 2 \cdot 10^{-11}$ [7]. Additionally, the unexpected high transparency of the universe for very high energy gamma rays could be caused by photon to ALP conversion in the B-field of the source or the intergalactic medium and subsequent ALP to photon back conversion close to or in our galaxy [8].

The allowed parameter range for Dark Matter ALPs is indicated in Fig. 1 as the area
below the green line. Additionally the ranges consistent with ALPs that could explain the cooling anomalies and the transparency hint are shown.

Presently no experiment has the sensitivity to detect Dark Matter axions in the mass range above \( \approx 40 \mu eV \) [4], thus, current experiments and ongoing efforts can neither cover the post inflationary Peccei-Quinn symmetry breaking scenario, nor the predicted axion mass for \( 2.4 < |\theta_i| < \pi \). Also the biggest part of the \( g_{ALP \gamma \gamma} \) vs \( m_{ALP} \) parameter space is still unexplored.

The MAquantized Disc and Mirror Axion eXperiment (MADMAX) has been devised to fill this experimental gap [9],[10]. It bases on the novel idea to use a configuration of many dielectric discs in front of a mirror inside a strong magnetic dipole field parallel to the disc surfaces [11]. Such a configuration uses conversion of Dark Matter axions or ALPs to electro-magnetic radiation at interfaces between media with different dielectric constants [12]. Stacking many disks with high dielectric constant in front of a mirror can significantly boost the axion induced expected signal of \( \approx 10^{-27} \text{W/m}^2 (10 \text{T})^2 \) to detectable levels of the order of \( 10^{-22} \text{W/m}^2 (10 \text{T})^2 \) in the QCD axion and ALPs mass range between 40 and 100 \( \mu eV \) [10]. For this a dipole magnet with a figure of merit of 100 \( \text{T}^2 \text{m}^2 \) is required. With this sensitivity range MADMAX will be complementary to cavity based experiments and to the solar axion experiment IAXO – with considerable CERN involvement, likely to be hosted at DESY, Hamburg - that will be sensitive to the QCD axion at masses >1 meV independent of cosmological assumptions.

MADMAX will consist of three parts: 1) The dielectric disks and the mirror – called the booster together with the optical system, 2) the receiver system including the amplifier chain and DAQ and 3) the superconducting dipole magnet surrounding the booster. A schematic sketch of the envisioned design is shown in Fig. 2 (not to scale). More details on the design ideas and first proof of principle investigations can be found in [10].

MADMAX will be hosted at DESY, Hamburg in hall north at the former site of the HERA detector H1. The existing iron yoke of the H1 experiment will be reused to shield the hall and equipment therein against the strong B-field and for stabilization of the B-field inside the magnet itself. The MADMAX project is being followed by the DESY Physics Research Committee (PRC). A detailed evaluation by the DESY PRC is scheduled for November 2019.

As a first step towards realization it is planned to build a prototype booster with reduced number and diameter of discs.

3 MADMAX prototype booster

The MADMAX prototype will be needed for investigating mechanical- and electromagnetic behavior of a scaled down booster. The prototype booster will be used to

1. verify the cryo-engineering;

2. test the achievable disk positioning accuracy;
3. test the understanding of the electromagnetic response;
4. qualify the necessary tiling of the disks;
5. verify operation of the booster in a high B-field;
6. potentially test for mechanical stability during magnet quench;
7. perform first physics searches for ALPs in an unexplored parameter space.

The MADMAX prototype will consist of a down scaled booster with 20 discs of 30 cm diameter each. It will be enclosed in a cryostat with a possible operating temperature from 300 down to $\approx 4$ K. Around the beam-path of the emitted signal the cryostat will have enough space to house the necessary optical system and to guide and focus the signal into
a cold preamplifier as the first stage of the receiver system. The optical system consists of the focusing mirror and a horn antenna as sketched in Fig. 3 (Top). This geometry ensures sufficient coupling of the receiver system to the beam for the specified frequency range with acceptable frequency dependent loss.

The preliminary rough design of a cryostat needed to keep the booster temperature and thus the system temperature seen by the receiver preamplifier at an acceptable level is in Fig. 3 (Bottom). The cryostat will have an outer diameter of < 1.5 m at the booster section, to allow to place the booster inside the MORPURGO magnet. The length of the beam path between end of the booster and the focusing mirror will be roughly 2.0 m and the distance between the focusing mirror and the horn antenna will be > 0.55 m.

The receiver used for the detection of the signal will be in an independent cryogenic containment, separated from the (prototype) booster cryostat by a flange containing the feedthrough for a horn antenna. The size of the receiver cryostat will be determined by the cooling technology chosen to keep the first stage amplifier at operational temperature but will likely not require more space than 2 m x 1 m.

The design of the prototype booster system as well as the booster cryostat are presently ongoing.

4 Potential use of the MORPURGO magnet at CERN

The MORPURGO magnet could be used to obtain crucial information on how the prototype booster system behaves in a high B-field magnet. The achievable B-field strength of the dipole magnet with 1.6 T, potentially up to 1.9 T, and its large warm bore aperture of 1.6 m presents a unique possibility for the testing of the MADMAX prototype. Operating the prototype booster inside such a field would allow to verify the impact of a strong B-field on the booster system. In particularly the effect of movement of the discs (Lorentz forces) and heat generation in the structural material (Eddy currents, etc.) could be studied. It should be noted that the forces exerted to the mechanical components scale with B^2. Thus, it would be desirable to operate the magnet at the highest achievable B-field.

Applying a B-field (dipole) to the booster parallel to the disk surfaces will also allow for a first search of ALPs with sensitivity on the ALP photon coupling down to \( \approx 10^{-12} \text{GeV}^{-1} \) at \( \approx 20 \) GHz and a frequency band of 200 MHz (\( \approx 1 \mu\text{eV} \)) within \( \approx 1 \) month of measurement time and roughly 1 GHz (\( \approx 5 \mu\text{eV} \)) within four months. Assuming that such ALPs make up all the dark matter this limit would exceed the sensitivity predicted by IAXO [18] see Fig. [1]. Again, the achievable sensitivity scales with B^2, hence would benefit from the B-field to be as high as reasonably possible.
5 Requirements for operation of the MADMAX prototype inside MORPURGO magnet

The required space necessary for the usage of the prototype booster inside the MORPURGO magnet is sketched in Fig. 4. Space would be required for the following components or activities:

1. the prototype booster plus receiver cryostat,
2. the required infrastructure to cool the booster components and the receiver (LHe dewars, pump systems, etc.),
3. DAQ, consisting of four racks,
4. Assembly and test areas,
5. Potentially: storage space for the prototype booster during non-availability of the MORPURGO magnet within the time periods April to December.

The specifications regarding electromagnetic noise to be met in order to be able to perform the search for ALPs are divided into the frequency ranges below and above 10 GHz. In general the setup could be operated with ambient EM noise power of:

Figure 4: Possible footprint of the prototype booster, the receiver cryostat and the DAQ space at North Area around the MORPURGO magnet.
• < -50 dBm for $f < 10$ GHz

• < -100 dBm for $f > 10$ GHz.

Dedicated long term measurement in different frequency ranges relevant for the planned MADMAX heterodyne detection scheme between 0 and 3 GHz were taken next to the MORPURGO magnet in North Area from March 8th until March 11th, 2019. Note that neither magnet nor the test beam was operational, hence, no signals related to these are expected. Except for the magnet not being on, the measurements should be typical for beam off periods. While considerable EM activity was detected in the sub GHz regime, in no frequency range the detected power was higher than the specifications. Short term measurements in the high frequency regime 10 to 26 GHz were performed. No signals could be detected. These measurements show that the EM background as determined in the measurement period is acceptable for measurement with the planned prototype booster setup.

The following infrastructural needs would arise:

1. Suitable experimental conditions: Good access to site (cleared access routes, scaffolding in front of MORPURGO,...), stable ground at site, no induction currents in floating surfaces, clean surrounding, damping of vibrations (due to crane movements, etc.);

2. Power for vacuum pumps: In total 3 pump stands will be needed: Insulation, booster vacuum and receiver cryostat, total power required $\approx 750$ W;

3. Supply for a LHe or dilution fridge: Power for dilution refrigerator $\approx 4$ kW (incl. cooling water);

4. LHe / LN supply for booster (and potentially receiver cooling if no chiller is used). It is foreseen to use transportable LHe dewars for cooling down the cryostats. The total amount of LN and LHe needed for cool-down of the booster cryostat is not yet known. Likely three 100 l LHe transport dewars used in circulation will suffice. This should be enough to also cool down and operate the receiver cryostat;

5. Exhaust/Recovery line for gaseous helium. Maximum evaporation rate will occur during cool-down of booster and receiver cryostat;

6. Power for DAQ (to be determined);

7. Crane operation (hooks for 10 t and 40 t are available and sufficient);

8. Ethernet;

9. Cable channels (experiment to racks, PC’s);
10. Cooling water for dilution refrigerator and/or vacuum pumps (depends on fringe field: if mag. shielding is needed, cooling by air is probably not sufficient).

6 Tentative schedule and open points

The MADMAX collaboration board has decided to start initiate further necessary steps for using the time slots of the CERN SPS shutdown Dec. 2021/22 and 2022/23 for mechanical tests of the prototype booster inside the MORPURGO magnet in the first place and potentially for physics measurements for the search of ALPs.

Provided a positive recommendation is expressed by the SPSC, further points will need to be addressed. Particularly the following points still have to be clarified:

- How can operational conditions at North area be met (required cleanliness, stable ground, avoid induction loops, etc.)?
- How and when can the maximum obtainable B-field be validated? Check, whether magnet operation at 1.9T is possible and measure fringe field in close environment.
- What infrastructural works are still needed? By whom and when could these works be performed?
- Availability of assembly and testing area close to MORPURGO?
- Can the experimental setup be stored in the north area when the magnet is not available for the MADMAX collaboration?

7 Tentative time schedule for integration into the MORPURGO magnet at CERN

The time schedule of the MADMAX prototype experiment is driven by the R&D needed for some booster components (especially Piezo motors and disk tiling development). A tentative time schedule is shown in Fig. 5. There is a risk that components to be developed

Figure 5: Possible footprint of the prototype booster, the receiver cryostat and the DAQ space at North Area around the MORPURGO magnet.
will need more R&D than initially thought. This implies that the schedule at present stage can’t be guaranteed and will be regularly updated on a half-yearly basis. It is therefore possible that measurements may continue after 2023.

References