Contribution Prospectives 2020

Search for axion dark matter with a novel approach used by the MADMAX experiment

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Abstract
Dark matter (DM) is one of the main puzzles in fundamental physics and axions are among the best-motivated DM candidates. Their discovery requires to develop new challenging detectors, among which MADMAX is the only one sensitive to the mass range favored by the theory from 40 to 400 μeV. Based on a novel concept of dielectric booster, MADMAX is entering an innovative R&D phase that should be concluded by the building of a prototype in 2021, possibly operated at CERN. The final detector will start taking data in 2025 in DESY-Hamburg with a high discovery potential. The work plan of possible IN2P3 participations to this experiment is initiated by CPPM contributions to the prototype. Such an ambitious and innovative project offers at low cost in the decade 2020-2030 a vast scientific potential coupled with several technological opportunities.

1. <u>Scientific and technological context</u>

The existence of dark matter, supported by a variety of astrophysical measurements, is one of the main puzzles in fundamental physics. However, as of today, the nature and properties of dark matter remain largely unknown, and their elucidation is APPEC Priority 5 (APPEC17). APPEC "*encourages the continuation of a diverse and vibrant programme (…) searching for Weakly Interacting Massive Particle (WIMP) and non-WIMP dark matter*" candidates. This contribution focuses on the latter possibility and discusses possible contributions in a recently proposed experiment, MADMAX (PBrun19_1), searching for a very well motivated dark matter candidate, the axion, currently uncovered at IN2P3.

The Peccei-Quinn axions (Peccei77; Weinberg78; Wilczek78) were postulated more than 40 years ago to explain the absence of CP violation in the strong sector, although it is allowed in the Standard Model (SM). Indeed, the SM controls CP violation in QCD by one fundamental parameter Θ, which can be inferred from the measurement of the neutron electric dipole moment (nEDM). As nEDM is currently not observed (Pendlebury15), a very strong upper limit is imposed $|\Theta| < 10^{-10}$. This experimental fact requires an extreme fine-tuning on Θ, which cannot be justified by anthropic reasoning. Axions are also excellent dark matter candidates (Preskill83; Abbott83; Dine83), provided their mass is in the range between 1 neV and 1 meV (Irastorza18).

So far, this mass range is practically unexplored, despite several attempts. The most competitive experiments rely on the conversion of the galactic halo (or solar) axions to photons under very intense magnetic fields (Sikivie83). The main challenge consists in boosting this extremely feeble microwave photon signal to be able to detect it with state of the art radiometers, which are sensitive up to the 10^{-22} W level. The ADMX experiment, a resonant cavity (boosting the signal) inserted in a high magnetic field, explored the mass range favored by the theory for the first time last year and probed a small mass region around 2 μeV (ADMX18). This experiment plans to cover the mass range from 2 to 10 μeV in the coming years. It is expected that the decade 2020-2030 will also see a systematic exploration of the theory-favored axion mass range from 10 μeV to 400 μeV, see Figure 1 (Irastorza18). This exploration will be based on improvement on the magnetic field strength as well as on novel concepts for the photon signal boost, which overcome the limitations from resonant cavities above 10 μeV.

Six years ago, new ideas proposed to escape from the cavity concept and instead use a magnetized dish antenna (Horns13) or movable magnetized disks with a high dielectric constant (Redondo13). First experimental realization of the dish antenna concept appeared in 2015 in a non-magnetic environment and an exploration of the hidden photon (a possible dark matter candidate) was possible in an unexplored range of 5-15 μeV (Suzuki15). More recently, colleagues from CEA/IRFU extended this range to 20-30 μeV with the SHUKET experiment (PBrun19_2). The dielectric disk booster concept is developed by the MADMAX collaboration, formed in 2017 and that gathers ~30 scientists from 8 institutes from Germany, Spain and France (CEA/IRFU). This experiment is aiming at a working detector for 2025. The goal is to explore the mass range between 40 and 400 μeV, favored by scenarios where the Peccei-Quinn symmetry is broken after inflation. MADMAX is presently the only experiment capable to discover the dark matter Peccei-Quinn axions in this favored mass range (Figure 1) and has very recently published a "white paper" (PBrun19_1).

The design of the MADMAX experiment is shown in Figure 2. The "booster" is composed of 80 disks (1 m diameter with 1 mm thickness, spaced out by 1.5 to 20 mm) with a very high dielectric constant (ε>20) located in a cryostat at very low temperature (4 K). The scan of the mass range is possible by gradually moving the disks from 1.5 to 20 mm using dedicated piezo motors located on rods and operating at cold. The cryostat, a cylinder of few meters long and 2-meter diameter, is immersed in a very high magnetic field (10 T), allowing to enhance significantly the conversion of galactic halo axions to photons. The photon signal, amplified by the booster (with a factor 10^5 with respect to a single magnetized mirror), is then directed with a focalizing mirror to a receiver chain, sensitive to high frequency (10-100 GHz) and very low power (10^{-22} W). The role of the booster is therefore central to be able to discover axions. In order to validate the fundamental concepts of the experiment and conclude on the technological options chosen for the booster, a prototype of smaller size will be built. Possibly operated at **CERN** in a lower magnetic field (1.5 T), it should be in a position to take data in 2022 and already constrain a still unexplored phase space (PBrun19_1). The final detector will start taking data in 2025 in DESY-Hamburg (within the DESY axion hub, together with IAXO (Armengaud14) and ALPS (Bähre13)) with a high discovery potential.

The schedule of the project is summarized in Table 1. The costs are estimated to be around 30 million euros.

	2019	2020	2021	2022	2023	2024	2025	≥2026
MADMAX	Preparation prototype	Construction prototype		Exploitation prototype		Construction final detector		Exploitation final detector

***Table 1**: Foreseen schedule for the MADMAX experiment.*

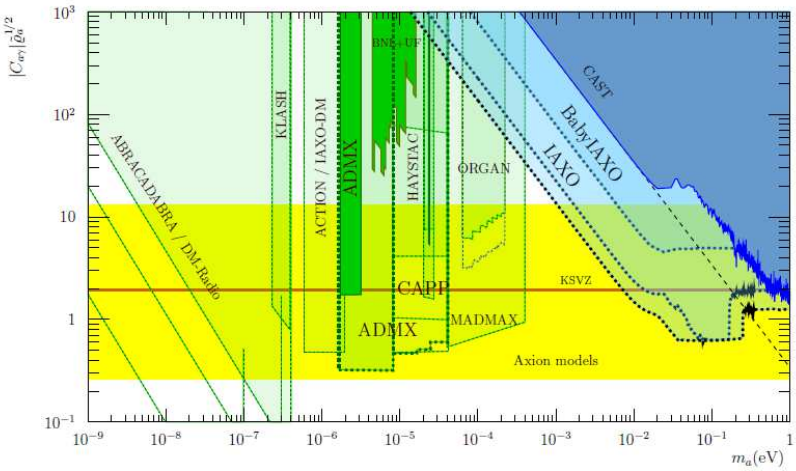

***Figure 1**: Exclusion regions from haloscope (in green) and helioscope (in blue) searches (Irastorza18). Some of the regions tentatively at reach in future experiments are indicated as semi-transparent green/blue areas. The yellow band and orange line represent the QCD axion models and the benchmark KSVZ model, respectively. Outside this yellow band, the axion does not solve the strong CP problem but remains a good dark matter candidate (they are then called axion-like particles or ALPs).*

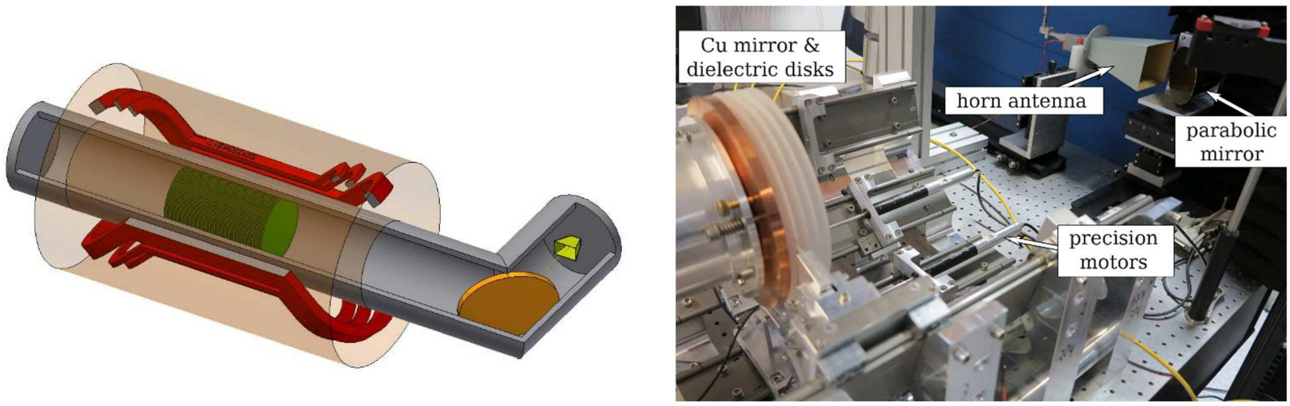

***Figure 2**: Left: Preliminary baseline design of the MADMAX approach, showing the magnet (red racetracks), the booster consisting of the mirror (copper disk at the far left), the 80 dielectric disks (green) and the system to adjust disk spacing (not shown) – and the receiver, consisting of the horn antenna (yellow) and the cold preamplifier inside a separated cryostat. The focusing mirror is shown as an orange disk at the right. Right: Picture of the proof of principle booster with 4 disks installed.* (PBrun19_1)

2. Technological and scientific opportunities for IN2P3 in 2020-2030

CEA/IRFU is a member of the MADMAX collaboration since its birth in 2017. Their contribution is focused on the design of the required dipole magnet. It should reach a B^2A value around 100 T^2m^2, which is unique and very challenging. This could be realized with a magnetic field strength of 10 T, with a bore of 1 m^2 allowing to host disks of similar size.

Since January 2019, CPPM is an associate member of the MADMAX collaboration. In the actual R&D phase, its efforts are focused on the realization of the booster and more specifically on the fabrication and characterization of the disks, composed of mono-crystals welded/glued together. In 2020-21, the work plan is therefore centered on the participation to the prototype booster (20 disks of 30 cm diameter) and the preparation to the prototype data analysis. In more details, the tentative plan is to pursue the following tasks:

1. Precision measurement of disks. To ensure a proper functioning of the booster, the disk planarity should be controlled at the 10 μm level. CPPM has already developed a recognized expertise in 3-dimensional measurements to build the pixel detector of the ATLAS experiment. It is planned to adapt this expertise to the prototype disks and perform measurements with two different methods (optical pen and laser scan). This will allow to improve the building process of the disks, and to validate the mechanical simulations.
2. Welding of mono-crystals. Lanthanum aluminate is presently envisioned as the baseline disk material for its high dielectric constant (ε=24). To be able to build 30 cm diameter stable disks with this material, hexagon mono-crystal tiles of few centimeters have to be glued together. This is currently the baseline option but welding techniques using laser are possible alternative options that CPPM will investigate.
3. Mechanical simulations. The design of the prototype booster should be scalable to the final detector. Thanks to the prototype disk measurements, it will be possible to adjust the simulations and check the potential problems arising when considering full-size disks. For instance, R&D on piezo motors that will be used to position the disks is still on-going with two possible options: disks moving on stable rods or disks fixed on moving rods. It is planned to choose the best solution by studying the scalability of these options, and compare them in terms of robustness and redundancy.
4. Participation to assembly, installation and commissioning of the prototype. The commissioning of the prototype will be shared in two parts. First, the assembly of the booster, installation in the cryostat and commissioning at room temperature and 4 K will take place next year in a dedicated experimental hall in Hamburg University and will last 1.5 years. The prototype booster assembled in the cryostat should then be shipped to CERN, integrated in a 1.5 T magnet in the North Area and commissioned during the shutdown periods of the SPS. Active commitments are expected during this period.
5. Preparation for physics analysis, simulations. Physics measurement in the 1.5 T magnet should start end of 2021 at CERN. To prepare the data taking and optimize the analysis strategy and the scientific output, strong involvements in the simulation program of the detector are needed. This is largely related to all other tasks, as the precise disk geometry, quality of the welding/gluing, mechanical behavior of the disks and quality of the commissioning obviously affect this physics output.

Such contributions initiate at IN2P3 an ambitious and innovative scientific and technological program paving the road toward the final MADMAX experiment, which will start taking data in 2025. More generally, the R&D program in the foreseen extreme conditions of the detector (vacuum, cryogenic temperature, high magnetic field) is ideal to develop new ideas and impulse dynamics on several fronts. These challenges towards the building of the detector imply innovative opportunities for IN2P3 technical departments to gather new expertise. As the detector will be assembled, installed and commissioned in Germany, collaborating closely with German institutes will offer us an opportunity to actively participate *in situ* to these operations and to be at the heart of the making of the experiment.

On the physics side, CPPM is initiating this very well motivated and promising field of experimental research at IN2P3. Participating actively to the medium-scale MADMAX experiment will allow us to increase the French visibility, at low cost with respect to the high discovery potential. The physics outcome will come first in 2022-2023 from the prototype data analysis that will look in a small but unexplored mass range of axion-like particles (PBrun19_1). Then, after 2025, the final detector will scan the most interesting phase space for the axion shown in Figure 1.

Last but not least, several synergies with other activities in CNRS and CEA/IRFU also exist. The NÉEL institute in Grenoble is a brand new associated member of the MADMAX collaboration that will share its expertise on the Josephson parametric amplifiers, a key element for the receiver. The SHUKET experiment lead by CEA/IRFU colleagues (see section 1) is planning for a second phase of operation within an intense magnetic field. Finally, colleagues from LNCMI-Toulouse are involved in a vacuum magnetic birefringence experiment using pulsed magnetic fields, potentially sensitive to axion-like particles (Cadene14).

3. Conclusions

The axion is one of the best motivated dark matter candidates, whose interest has gained significant momentum in the last decade. We consider its search, to which IN2P3 is so far absent, as a scientific priority in the DM field. In this context, the MADMAX project is presently the only experiment capable to explore the mass range between 40 and 400 μeV, favored by scenarios where the Peccei-Quinn symmetry is broken after inflation. It therefore has a high discovery potential. Its main first scientific target is to conceptualize, build and commission a prototype (2021), which paves the road towards the final detector (2025).

Such an ambitious and innovative project offers a healthy mix to IN2P3 in the decade 2020-2030, reinforcing the European leadership in this worldwide effort: a vast scientific potential coupled with several technological opportunities, and possible synergies with other CNRS institutes. The great discovery potential can be performed with investments much below the scale of accelerator-based detectors. This could re-vitalize the experimental landscape and attract both young as well as established physicists into the field. This is moreover complementary to ongoing IN2P3 involvment in direct searches for WIMPs.

The experiment is presently in an innovative R&D phase, which is ideal to impulse dynamics on several technological fronts in the technical departments of the institute. Moreover, contributions to an experiment operated in large international laboratories (CERN for the prototype and DESY for the final detector) gives to students the opportunity to be trained in a rich and stimulating international environment.

Last but not least, this program is in line with statements from the last APPEC strategic document (see section 1) and from the October 2018 IN2P3 scientific council: "*Il faut noter que les axions sont un candidat générique à la matière noire, également physiquement motivé, et ce depuis plusieurs dizaines d'années. L'un des piliers des WIMPs étant mis à mal par l'absence de signe de nouvelle physique dans les résultats du LHC, cette alternative doit être gardée à l'esprit (…)*"

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