PROCEEDINGS OF SCIENCE

Towards a tunable mK haloscope in RADES

Jose-María García-Barceló,[a,*] **C. Cogollos**[a] **and B. Döbrich**[a]

[a] *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)*
Boltzmannstraße 8, 85748 München, Germany

E-mail: jmgarcia@mpp.mpg.de

Within the framework of the CAST experiment at CERN, a new experimental group for developing haloscopes in search of dark matter axions emerged in 2016, the RADES collaboration, which has pioneered several multicavity technologies for these detectors. Recently, a new group appeared at MPP in 2022 and has carried out over the last year axion detection research, including the design and fabrication of a mechanically tuned 9 GHz resonant cavity that will be installed in a 10 mK temperature and 12 T magnetic field cryostat. This work describes the updates of the research carried out in this project and other RADES collaborators.

2nd Training School and General Meeting of the COST Action COSMIC WISPers (CA21106) (COSMICWISPers2024)
10-14 June 2024 and 3-6 September 2024
Ljubljana (Slovenia) and Istanbul (Turkey)

*Speaker

PoS(COSMICWISPers2024)044

1. Introduction

Axion particles are dark matter candidates that could also solve the strong CP problem [1–4], and they have been searched for the last decades by many experiments. If they exist, they could be dark matter in the mass range between 1 and 1000 μeV. Although their interaction would be very weak, it is thought that axion-photon coupling should exist in the vanilla axion models, thus opening a window for their detection. The conversion concept is based on the so-called inverse Primakoff effect [5]. In the case of haloscopes, which search for axions that would have been created in the early universe and that would constitute the galactic halo (often referred to as *relic axions*), they employ high-Q microwave cavity technologies immersed in high magnetic fields to enhance this axion-photon conversion [6]. There are other axion detectors, such as helioscopes, which direct their detectors towards the sun as they try to detect axions that may have been created inside the star.

Examples of current haloscope experiments include ADMX [7] and CAPP [8], which search for axions at frequencies below and above 1 GHz, respectively, with remarkable sensitivities. Other collaborations looking for axions at other axion masses (or frequencies) are HAYSTAC [9, 10], QUAX [11, 12], and FLASH [13, 14]. RADES (*Relic Axion Detection Exploratory Setup*) is a collaboration of different universities and research centres worldwide, created in 2016 within the framework of the CAST (*CERN Axion Solar Telescope*) experiment for the search for dark matter axions with haloscopes [15]. Its main milestone was based on the implementation of the multicavity concept in haloscopes in order to increase their volume without reducing the frequency, a problem that has long persisted in the axion community. Also, the CAPP team developed and implemented an efficient high-frequency haloscope using a multi-cell cylindrical cavity method [16, 17]. This method reinforces the volumetric growth of the haloscopes while maintaining the operating frequency. To date, the RADES team has carried out 3 campaigns of axion measurements with haloscopes. The first one was done at the CAST dipole magnet (experimental volume with 9 T of magnetic field at 1.9 K) in 2018 with a multicavity based on 5 subcavities operating at 8.38 GHz, the results of which were published in [18]. The second one was at CERN-SM18 (11.7 T at 1.9 K) in 2021 with an HTS (High-Temperature Superconducting) cavity operating at 8.84 GHz, obtaining a small tuning range due to pressure changes in the helium (see results in [19]). The last data acquisition was recently carried out with an improved HTS cavity (higher quality factor) and setup at SM18 again, and its results are currently under analysis.

Section 2 describes the experiments conducted at the RADES subgroup at the Max Planck Institut für Physik (*RADES-MPP*). Section 3 shows the updates from other teams in the RADES collaboration. Finally, Section 4 gives conclusions and future lines of work for these experiments.

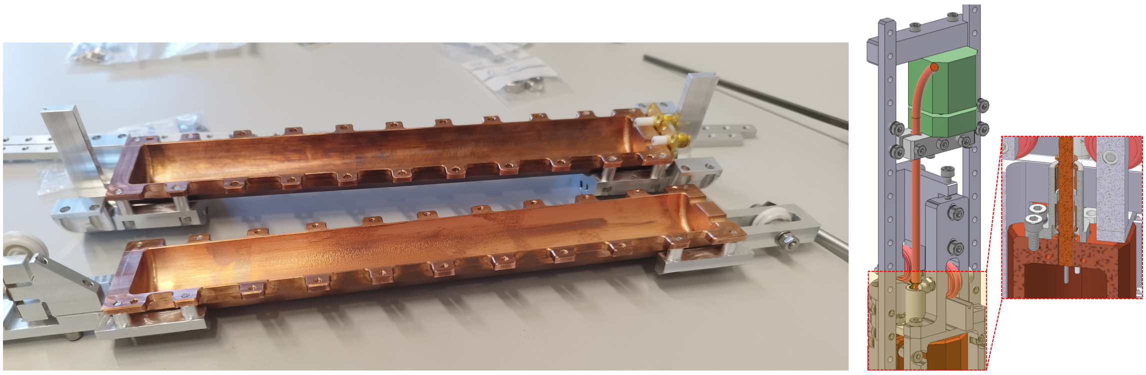
2. RADES-MPP team

The RADES-MPP group has carried out several studies related to axion haloscopes. Each of them is detailed below.

PoS(COSMICWISPers2024)044

2.1 Cylindrical cavity with vertical cut tuning

One of the main projects in this team was the design, simulation, fabrication, and electromagnetic characterisation of a resonant cylindrical cavity operating at 9 GHz with the TM_{010} mode (height of 200 mm and diameter of 25.5 mm), with a frequency tuning system based on its vertical fabrication cut, achieving a shift in frequency by adjusting the gap between the two fabricated halves of the cavity. In the axion community, one of the most commonly used frequency tuning systems is the insertion and rotary movement of rods inside the resonant cavities, thus modifying their electromagnetic field and thus the resonant frequency. However, it has been seen that this tuning system with vertical cut provides improvements in terms of form factor, quality factor, and tuning range [20]. In Figure 1a a picture of the manufactured cavity with its tuning assembly is shown.



(a) (b)

Figure 1: (a) Manufactured housing of the cylindrical cavity (based on two symmetrical halves) with the vertical cut. The cavity is attached to some pieces of its tuning system assembly. Two cavity versions have been manufactured, one in standard copper and the other in OFHC (Oxygen-Free High Conductivity) copper for better thermalization. (b) 3D model of the coupling readjustment system.

This type of vertical cut, which has been previously used on rectangular and quasi-rectangular cavities in RADES (see [20] and [21]), allows to reduce the quality factor detriment that occurs when fabricating a resonant cavity structure. Moreover, in this collaboration, frequency tuning has been previously carried out by inserting different gaps in this cut (the larger the gap, the lower the resonant frequency) in a rectangular multicavity [20]. However, it has never before been carried out in cylindrical cavities, the most widely used geometry in the axion community, because of its adaptation to the experimental space in the magnets used for data acquisition.

An extensive study of this cylindrical cavity and its performance in quality factor and form factor, key parameters in a haloscope experiment, with this tuning system has been carried out in this subgroup. These studies involve the characterisation of the cavity at room temperature (300 K) and cryogenic (4 K) with different systems with motors (for the gap adjustment) adapted to these temperatures. Also, a bead-pull measurement has been conducted for the extraction of the real electric field patterns, providing a measurement for the form factor parameter and the identification of the axion mode. We plan to use this cavity for axion data acquisition in a system reaching mK temperatures, which will be explained in the following section.

In addition, an input/output coupling readjustment system (β parameter) has been developed, given by the introduction of the port antennas (coaxial SMA panel for our case) inside the cavity volume (see Figure 1b). The value of β is an important parameter in a data campaign with haloscopes, and, in a system with frequency tuning, its continuous adjustment is needed since it varies with the frequency and must be kept fixed ($\beta = 2$). The developed system consists of the movement of a semi-rigid coaxial cable through a holder with finger gaskets (to maintain the position without high friction) on one port, thanks to a motor or positioner (different according to the temperature of our experiment, at 300 K, 4 K or mK). Several studies have been carried out, the data of which are currently being analysed.

2.2 LD-250 dilfridge system

As discussed in Section 1, the RADES collaboration has carried out 3 campaigns of axion measurements, all of them in cryostats with temperatures above 1.9 K. Today, several experimental groups in the axion community make use of dilfridge systems that reduce temperatures to levels of about 10 mK. Recently, the RADES-MPP group has acquired and installed a Bluefors dilfridge system (the LD-250 system [22]) with a solenoid magnet implemented inside. Figure 2a shows a picture of this system's different stages (plates) of thermalisation, being the bottom one, the mK plate. The installation of the solenoid magnet in this system, together with various shieldings, is shown in Figure 2b. The experimental space (see Figure 2c), where the RADES cavity can be installed, is about 400 mm in length and 68 mm in diameter. The cavity described in the previous section has been designed with the dimensions of this space in mind, as axion data are to be taken with such a haloscope in this system.

(a) (b) (c)

Figure 2: (a) Plates of the Bluefors LD-250 dilfridge system: *50 K* plate ($T \approx 40$ K), *4 K* plate ($T \approx 2$ K), *Still* plate ($T \approx 750$ mK), *CP* plate ($T \approx 200$ mK), and *MXC* plate ($T \approx 7$ mK). (b) Encapsulation of some of the plates and installation of the solenoid magnet (grey structure at the bottom). (c) 3D model of the cross-section in the region of the experimental cylindrical space (area illuminated in red).

This cryostat has already been installed in the RADES-MPP laboratory, giving $T \approx 10$ mK with $B = 12$ T when the experimental volume is empty. The next steps focus on implementing

PoS(COSMICWISPers2024)044

quantum noise-limited amplifiers, developing a haloscope setup, experimenting with single photon counting, and the first axion data campaign at MPP.

2.3 Other studies

Also, at the RADES-MPP group, we are assisting with the analysis of data taken in the axion data campaigns within the RADES collaboration (the last one being the one taken in November 2024). For this, the stored data are post-processed in software by eliminating systematic errors, unifying spectra, and implementing fits to find out whether the axion has been found or not. If the axion is not found, a new limit is set in the electromagnetic spectrum.

3. Other activities in the RADES collaboration

RADES is a collaboration with common goals, like quantum limited axion detection. We are carrying out tasks related to 3 topics or *Working Groups* (WG): *WG-cavities*, *WG-analysis*, and *WG-detection*. For example, the RADES-UPCT/UV group is developing low-frequency cavities ($f \approx 300$ MHz), with relatively large dimensions (2×5 meters long cavities) to be installed in the future in the BabyIAXO experiment, which will have an experimental space of 600 mm in diameter and 10 m in length [23]. In addition, research is being done on other R&D strains in the axion community, such as the implementation of superconducting materials (HTS), electrical tuning with varactors, tuning with ferroelectric [24] and ferromagnetic materials, use of metamaterials, the design of new cavity topologies with higher volume and quality factor [25, 26], and the development of cavities for the detection of gravitational waves at microwave frequencies [27].

On the other hand, the RADES-Mainz group has developed the SUPAX experiment, based on a haloscope operating around 8.3 GHz at 4 K temperature developed for the search of dark photons at masses of 34 μeV. The first results are published in [28].

4. Conclusions and future work

The RADES group has made several advances in haloscope experiments, like the development of cavities for different frequencies, the implementation of several setups in cryogenic systems, or the analysis of data from axion campaigns. In particular, the RADES-MPP group is taking a next step with the implementation of a tunable haloscope that plans to be installed in a 10 mK temperature system with 12 T magnetic field for axion data taking.

Some of the future lines inside this team are the development of a data acquisition protocol for this tunable haloscope, the acquisition and performance tests of quantum-limited amplifiers (*Travelling Wave Parametric Amplifier* or *TWPA*), and the investigation of single photon (Qubit devices) readout technologies in the framework of the QuantERA-QRADES [29] project.

Acknowledgments

This work was performed within the RADES group and we gratefully acknowledge their support. Additionally, we would like to thank the MPP workshop, especially David Kittlinger, for the design of the mechanical cavity structures. JMGB thanks the European Research Council grant ERC-2018-StG-802836 (AxScale project) and the Lise Meitner program "In search of a new, light physics" of the Max Planck Society. This article is based on the work from COST Action COSMIC WISPers CA21106, supported by COST (European Cooperation in Science and Technology).

References

[1] Steven Weinberg. A New Light Boson? *Phys. Rev. Lett.*, 40:223–226, Jan 1978.

[2] F. Wilczek. Problem of Strong P and T Invariance in the Presence of Instantons. *Phys. Rev. Lett.*, 40:279–282, Jan 1978.

[3] R. D. Peccei and Helen R. Quinn. Constraints imposed by CP conservation in the presence of pseudoparticles. *Phys. Rev. D*, 16:1791–1797, Sep 1977.

[4] R. D. Peccei and Helen R. Quinn. CP Conservation in the Presence of Pseudoparticles. *Phys. Rev. Lett.*, 38:1440–1443, Jun 1977.

[5] H. Primakoff. Photo-Production of Neutral Mesons in Nuclear Electric Fields and the Mean Life of the Neutral Meson. *Phys. Rev.*, 81:899–899, Mar 1951.

[6] P. Sikivie. Experimental Tests of the "Invisible" Axion. *Phys. Rev. Lett.*, 51:1415–1417, Oct 1983.

[7] I. Stern. ADMX Status. *PoS*, ICHEP2016:198, 2016.

[8] Andrew K. Yi et al. Axion Dark Matter Search around 4.55 μeV with Dine-Fischler-Srednicki-Zhitnitskii Sensitivity. *Phys. Rev. Lett.*, 130:071002, Feb 2023.

[9] L. Zhong et al. Results from phase 1 of the HAYSTAC microwave cavity axion experiment. *Phys. Rev. D*, 97:092001, May 2018.

[10] K. M. Backes et al. A quantum-enhanced search for dark matter axions. *Nature*, 590(7845):238–242, 2021.

[11] D. Alesini et al. Search for invisible axion dark matter of mass $m_a = 43$ μeV with the QUAX–$a\gamma$ experiment. *Phys. Rev. D*, 103:102004, May 2021.

[12] D. Alesini et al. Realization of a high quality factor resonator with hollow dielectric cylinders for axion searches. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 985:164641, 2021.

[13] David Alesini, Danilo Babusci, Daniele Di Gioacchino, Claudio Gatti, Gianluca Lamanna, and Carlo Ligi. The KLASH Proposal, arXiv:1707.06010 [physics.ins-det], 2017.

[14] David Alesini et al. The future search for low-frequency axions and new physics with the FLASH resonant cavity experiment at Frascati National Laboratories. *Physics of the Dark Universe*, 42:101370, 2023.

PoS(COSMICWISPers2024)044

[15] Alejandro Díaz-Morcillo et al. Design of new resonant haloscopes in the search for the dark matter axion: A review of the first steps in the rades collaboration. *Universe*, 8(1), 2022.

[16] Junu Jeong, SungWoo Youn, Sungjae Bae, Jihngeun Kim, Taehyeon Seong, Jihn E. Kim, and Yannis K. Semertzidis. Search for invisible axion dark matter with a multiple-cell haloscope. *Phys. Rev. Lett.*, 125:221302, Nov 2020.

[17] Junu Jeong, Sungwoo Youn, and Jihn E. Kim. Multiple-cell cavity design for high mass axion searches: An extended study. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 1053:168327, 2023.

[18] A. Álvarez Melcón et al. First results of the CAST-RADES haloscope search for axions at 34.67 μeV. *JHEP*, 21:075, 2020.

[19] S. Ahyoune et al. RADES axion search results with a High-Temperature Superconducting cavity in an 11.7 T magnet, arXiv:2403.07790 [hep-ex], 2024.

[20] Jessica Golm, Jose María García-Barcelo, Sergio Arguedas Cuendis, Sergio Calatroni, Walter Wuensch, and Babette Dobrich. Split-cavity tuning of a rectangular axion haloscope operating around 8.4 GHz. *Frontiers in Physics*, 12, 2024.

[21] J. Golm et al. Thin Film (High Temperature) Superconducting Radiofrequency Cavities for the Search of Axion Dark Matter. *IEEE Transactions on Applied Superconductivity*, 32(4):1–5, 2022.

[22] Bluefors LD Dilution Refrigerator Measurement System, 2024. Last accessed 9.12.2024.

[23] Saiyd Ahyoune et al. A Proposal for a Low-Frequency Axion Search in the 1–2 eV Range and Below with the BabyIAXO Magnet. *Annalen der Physik*, 535(12):2300326, 2023.

[24] J. M. García-Barceló et al. On the Development of New Tuning and Inter-Coupling Techniques Using Ferroelectric Materials in the Detection of Dark Matter Axions. *IEEE Access*, 11:30360–30372, 2023.

[25] J. M. García-Barceló et al. Methods and restrictions to increase the volume of resonant rectangular-section haloscopes for detecting dark matter axions. *JHEP*, 08:098, 2023.

[26] J. M. García-Barceló, A. Díaz-Morcillo, and B. Gimeno. Enhancing resonant circular-section haloscopes for dark matter axion detection: approaches and limitations in volume expansion. *JHEP*, 11:159, 2023.

[27] José Reina Valero et al. High-frequency gravitational waves detection with the BabyIAXO haloscopes, arXiv:2407.20482 [hep-ex], 2024.

[28] Tim Schneemann, Kristof Schmieden, and Matthias Schott. First results of the SUPAX Experiment: Probing Dark Photons, arXiv:2308.08337 [hep-ex], 2023.

[29] `https://quantera.eu/qrades/`.

PoS(COSMICWISPers2024)044