Journal of Low Temperature Physics
https://doi.org/10.1007/s10909-025-03274-7

A Low Background Setup for Low Energy X-ray Detection in the Context of the BabyIAXO/IAXO Axion Searches

M. Loidl[1] · E. Ferrer-Ribas[2] · L. Gastaldo[3] · Arshjot Kaur[1] · S. Kempf[4,5] · X.-F. Navick[2] · M. Rodrigues[1] · M. L. Zahir[1]

Received: 3 November 2023 / Accepted: 23 January 2025

Abstract
In the context of axion search in the BabyIAXO and IAXO helioscopes, various types of cryogenic detectors are investigated as high energy resolution, low energy threshold alternatives for the standard micromegas X-ray detectors. The setup presented in this paper comprising metallic magnetic calorimeter (MMC) X-ray detectors, a cryogenic local muon veto read out by an MMC, and internal and external lead shields, aims at establishing the background level that can be reached with MMCs in an above-ground experimental site. The low background setup is described in detail, and first observations from a low-temperature run are presented.

Keywords Low background · Metallic magnetic calorimeter · Axion search

1 Introduction

BabyIAXO, fully funded and presently under construction, and the future IAXO experiment, are next generation helioscopes for solar axion search [1]. According to the best predictions, solar axions should convert, in the helioscope's magnetic field, to photons in the energy range ~ 0.5–10 keV. The baseline photon detectors are based on microbulk micromegas detectors, a well-established and robust technology

✉ M. Loidl
martin.loidl@cea.fr

1 Université Paris-Saclay, CEA, List, Laboratoire National Henri Becquerel, Bat. 602, CEA-Saclay, 91120 Palaiseau, France

2 CEA, Institut de Recherche sur les Lois Fondamentales de l'Univers, Université Paris-Saclay, 91191 Gif-sur-Yvette, France

3 Heidelberg University, Kirchhoff Institute for Physics, Heidelberg, Germany

4 Institute of Micro-and Nanoelectronic Systems, Karlsruhe Institute of Technology, Hertzstraße 16, 76187 Karlsruhe, Germany

5 Institute for Data Processing and Electronics, Karlsruhe Institute of Technology, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany

Published online: 11 February 2025

proven in the CAST helioscope [2]. They have, however, a relatively high energy threshold (1–2 keV) and modest energy resolution. In particular if an axion signal should be observed, the detailed study of its energy spectrum would require very low threshold, high energy resolution X-ray detectors. Therefore, several alternative detector technologies are being explored: GridPix, an upgrade of Micromegas detectors, silicon drift detectors (SDDs), and three types of cryogenic detectors—germanium wafers with neutron transmutation-doped (NTD) Ge thermistor as well as transition edge sensor (TES) readout, and pixelated MMC X-ray detectors.

BabyIAXO and IAXO will be hosted in an above-ground hall at DESY. While it is quite straightforward to achieve very high energy resolutions and low energy thresholds with cryogenic detectors, reaching a low enough background level is challenging: the required background levels are about 10^{-7} keV^{-1} cm^{-2} s^{-1} for BabyIAXO and ~ 10^{-8} keV^{-1} cm^{-2} s^{-1} for IAXO. In this paper, we present a dedicated low background setup developed to determine to which background level one can descend with MMC X-ray detectors operated in an above-ground laboratory.

2 The Low Background Test Setup

Apart from using low radioactivity materials for the construction of the detector setup itself, internal and external shielding of the cryostat reduce the background due to ambient radioactivity, and an inner, cryogenic muon veto was devised to minimize the cosmic muon-induced background.

2.1 Shielding

The external shielding consists of 10-cm lead underneath and around the helium dewar of the dilution refrigerator up to a height of 1.50 m, providing a solid angle coverage with respect to the X-ray detector position inside the cryostat of ~ 98.8%. The dilution refrigerator available at the Laboratoire National Henri Becquerel (LNHB) has an experimental space of 90 mm diameter, leaving room for a 5-mm-thick inner lead shielding cylinder. At the top of the experimental space, a 2-cm-thick lead disk was screwed to the mixing chamber plate. It fully covers the lacking solid angle of the external shielding. The internal lead shielding (total mass ~ 4.1 kg) was made from ~ 100 years old lead with a ^{210}Pb content measured at Canfranc underground laboratory as (2.27 ± 0.69) Bq/kg, about a factor 30 lower than modern lead. Inside the lead cylinder, a 3-mm-thick cylinder from CuC2 high radiopurity copper was placed, and below the top lead disk a 5-mm-thick CuC2 copper disk.

2.2 Muon Veto

As a muon veto, a 2″ (50.8 mm) diameter, 1-mm-thick high purity Ge wafer is used. It has four 7-mm-diameter, 200-nm-thick gold films, evaporated on one of its faces, acting as phonon collectors. The gold films are thermally coupled via 25-μm-diameter gold bonding wires to one of the Ag:Er sensors of an “M-size”

MMC chip from the MetroMMC project [3], an upgraded version of the MMCs developed in the MetroBeta project [4, 5]. The wafer is held by PTFE pieces and is placed 2 mm above the X-ray detector MMCs. Since downgoing as well as upgoing muons interacting in the X-ray MMCs do also cross the wafer, with its 2″ diameter, it provides a nearly 4π solid angle; only muons with a practically horizontal trajectory could be missed. The actual solid angle coverage is 91%. Using the angular distribution of the cosmic muon flux with a $\cos^n \Theta$ dependency on the zenith angle Θ and $n=2.1$ from [6], and supposing nearly 100% efficiency for muons crossing the wafer, a conservative estimation of the total veto efficiency gives 99.8%. * MERGEFORMAT Fig. 1 shows the wafer with the circular gold films and the MMC and SQUID (superconducting quantum interference device) chips on a copper bridge just above the wafer. The chips were glued to the copper holder with an Araldite epoxy glue known to have very low radioactive contaminations.

2.3 X-ray Detector MMCs

To establish a background rate within a measurement campaign not exceeding a few weeks, an X-ray detection active area of the order 1 cm^2 is desirable, corresponding to the area of the BabyIAXO X-ray focal plane. Since the wiring of the LNHB dilution refrigerator is limited to 10 MMC and SQUID channels, highly pixelated MMCs are not the best choice for this test program. We decided to use MetroMMC "L-size" MMCs, each sensor being equipped with a 2.05×4.1 mm^2 area, 20-µm-thick gold absorber (detection efficiency of 99% at 10 keV [7]); six of these MMCs have a summed active area of 1 cm^2. Two MMCs with four X-ray absorbers and the corresponding two SQUIDs are placed underneath one common muon veto wafer. In the first stage, we ran a test with one module of muon veto wafer + 2 X-ray MMCs. In an upcoming run the full setup with three modules (Three muon veto wafers, six X-ray MMCs with a total active area of 1 cm^2) plus a fourth muon veto wafer below the lowest X-ray detector layer, read out with a total of 10 MMCs and 10 SQUIDs, will be implemented. A cross-sectional sketch of the full setup is shown

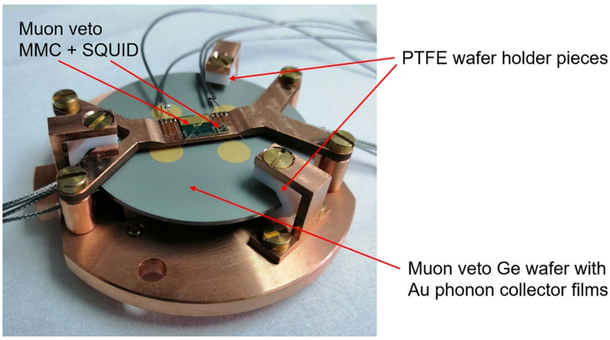

Fig. 1 (Color online) The muon veto comprising a germanium wafer with Au phonon collector films, and an MMC and a SQUID chip on a copper bridge. The phonon collector films are thermally coupled to one of the MMC sensors via gold bonding wires. The PTFE wafer holder pieces are configured such that due to their thermal shrinkage while cooling the wafer is held more tightly and vibrations are reduced

in * MERGEFORMAT Fig. 2. All copper parts (apart from the internal shielding) were made from CuC1 copper of high radiopurity. The X-ray detectors can be seen in * MERGEFORMAT Fig. 3.

3 First Test

The conditions during the first test run were far from optimal. Firstly, the setup was not entirely prepared for a low background measurement. At the time of the first assembly, no copper screws were available, so we used standard brass screws, visible in * MERGEFORMAT Fig. 1 and * MERGEFORMAT Fig. 3, with an undetermined impurity level. The cables connected to the MMC and SQUID chips are themselves rather radiopure, as a measurement at the Canfranc underground lab has revealed [8]. However, they were soldered to the detector holder with standard PbSn solder not reduced in ^{210}Pb. The quantity of solder is very small, but some of the solder points are very near the X-ray MMCs. Therefore, in principle, it cannot be excluded that they contribute to the background.

Secondly, due to an error in the settings of the SQUID electronics, the data acquisition was not operating correctly during this first test, and there were periods in which one or the other channel (X-ray or veto) was not recording data. Under these conditions, no background rate could be determined.

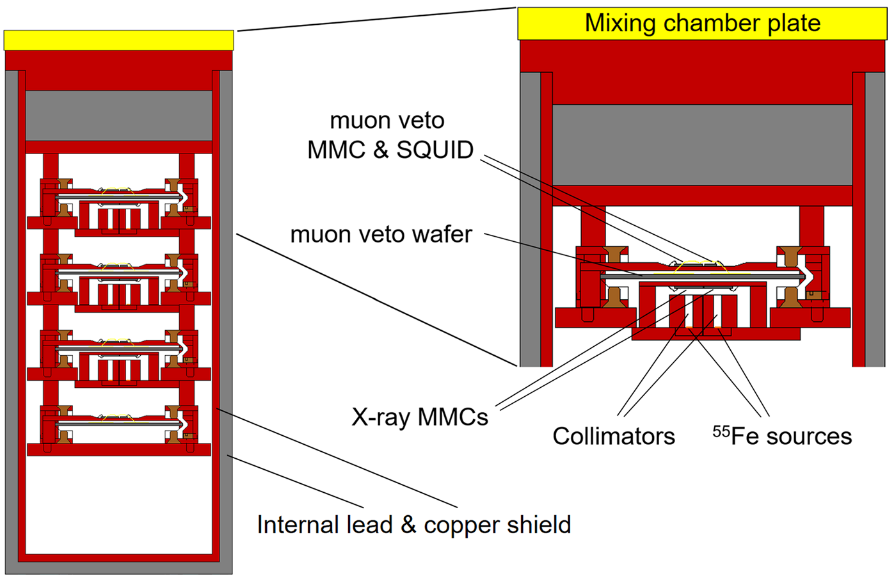

Fig. 2 (Color online) Complete low background test setup with internal lead and copper shield. On the right, a zoom to the topmost of the three modules with one muon veto wafer and two X-ray MMCs. To establish the energy scale and to test the detector performance, low activity ^{55}Fe sources can be placed facing the X-ray detectors and collimated to their Au absorbers

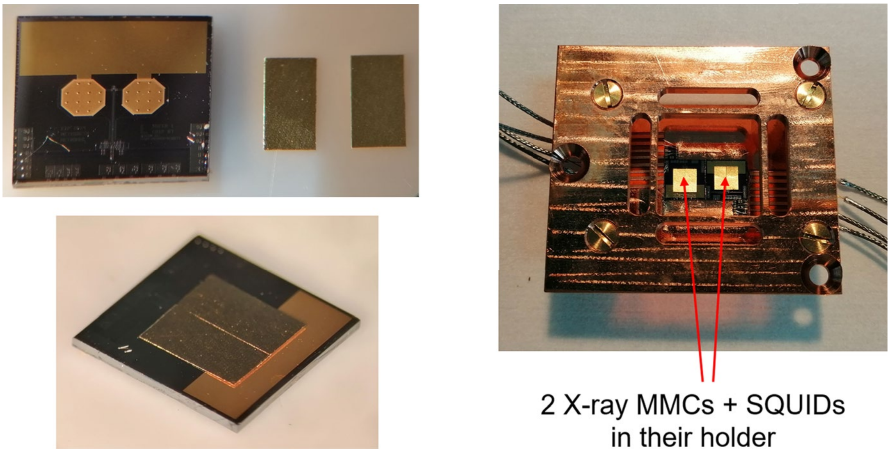

Fig. 3 (Color online) *Top left:* MetroMMC L-size MMC chip [3–5] and two 2.05 × 4.1 mm^2 gold absorbers. *Bottom left:* The absorbers were glued to the Ar:Er sensors with four small Araldite epoxy drops placed between the gold stems on each sensor. *Right:* Two X-ray detector MMCs and two SQUID chips placed in their copper holder

Thirdly, one of the two X-ray MMCs must have been contaminated: it had a count rate of approximately 1 s^{-1}, with a broad distribution of pulse heights, while the other MMC exhibited a much lower count rate (see below).

Nevertheless, the test has shown that the muon veto seems to work rather efficiently. Without the external 10-cm lead shielding, each 8 mm^2 absorber received ~ 3 counts/min. With the external lead shielding in place, the rate decreased to ~ 0.3 counts/min, and during a ~ 1 h observation on an oscilloscope, they were all in coincidence with the muon veto. * MERGEFORMAT Fig. 4 displays a pulse in one of the X-ray MMC absorbers in coincidence with a pulse in the muon veto. There were also very small pulses with long rise times (~ 2 ms vs. ~ 20 µs for absorber events) observed in the X-ray channel, also in coincidence with the muon veto, as shown in

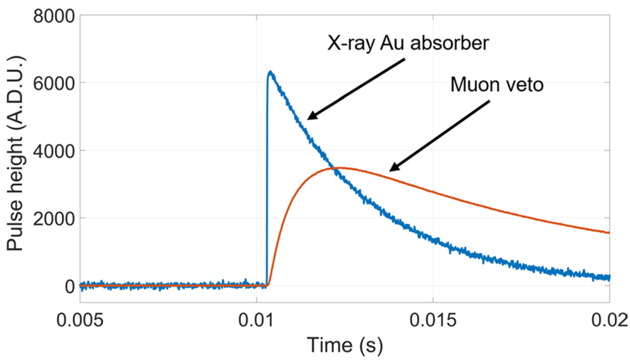

Fig. 4 (Color online) Coincident pulses in the X-ray Au absorber and in the muon veto wafer

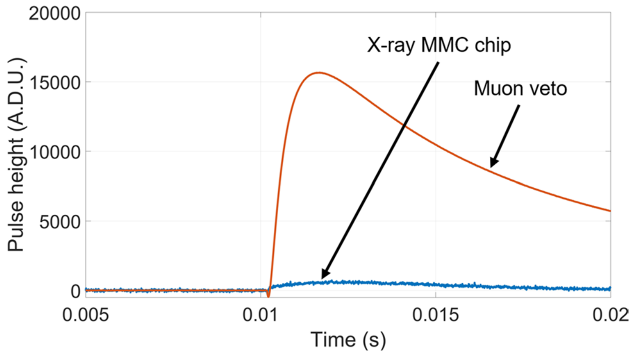

Fig. 5 (Color online) Coincident pulses in the X-ray MMC chip and in the muon veto wafer

* MERGEFORMAT Fig. 5. These can be identified as muons depositing energy in the MMC chip outside of the absorber area and seen by the sensor as a phonon signal.

After 17 h of data acquisition, there were about 30 pulses only visible in the (non-contaminated) X-ray MMC, without any signal in the veto channel. We cannot state how many of them are true background events, some of them certainly due to the contamination present on the second MMC, and how many are due to the above mentioned problem with the acquisition of the veto channel at the respective instants.

4 Conclusion

In the context of the BabyIAXO and IAXO helioscopes for solar axion search, a low background test setup has been developed to determine the background level that can be achieved with MMCs operated in an above-ground laboratory. It comprises shieldings outside and inside the dilution refrigerator and an internal, cryogenic muon veto. The muon veto appears to be rather efficient. In the presented version, the setup was assembled with brass screws. These will be replaced by low radioactivity copper screws in the next test run. Likewise, the cables soldered with standard PbSn solder to the detector holder will be replaced by Kapton/copper ribbon cables with bond contacts directly connecting the ribbon cables to the MMC, respectively, SQUID chips. In the presented state, the setup was composed of one muon veto wafer and two X-ray detector MMCs. The full setup will comprise three such modules with a total X-ray detection area of 1 cm^2.

Acknowledgements We would like to warmly thank Susana Cebrián Guajardo from Universidad de Zaragoza and staff from Canfranc underground laboratory for the screening of the lead used for the inner shielding as well as the low-temperature cables. We acknowledge support from the Agence Nationale de la Recherche (France) ANR-19-CE31-133 0024.

Author contributions M. Loidl—Development of the detector setup; wrote the main manuscript text E. Ferrer-Ribas—Project leadership (PI), and management L. Gastaldo—MMC development for IAXO A.

Kaur—Radioactive source preparation S. Kempf—MMC chip design and microfabrication X-F. Navick -Took care of provision of low background materials M. Rodrigues—Data analysis M. L. Zahir—Configuration of a chip test device and chip tests. All authors reviewed the manuscript.

Funding Open access funding provided by Commissariat à l'Énergie Atomique et aux Énergies Alternatives.

Declarations

Conflict of interest The authors declare no competing interests.

References

1. A. Abeln et al., Conceptual Design of BabyIAXO, the intermediate stage towards the international Axion observatory. J. High Energy Phys. **5**, 137 (2021). https://doi.org/10.1007/JHEP05(2021)137
2. CAST collaboration, "New CAST limit on the axion–photon interaction", Nature Physics 13, 584–590 (2017), https://doi.org/10.1038/NPHYS4109
3. P.C.-O. Ranitzsch et al., MetroMMC: electron-capture spectrometry with cryogenic calorimeters for science and technology. J. Low Temp. Phys. **199**, 441 (2020). https://doi.org/10.1007/s10909-019-02278-4
4. M. Loidl et al., MetroBeta: beta spectrometry with metallic magnetic calorimeters in the framework of the European program of ionizing radiation metrology. J. Low Temp. Phys. **193**, 1251 (2018). https://doi.org/10.1007/s10909-018-1933-0
5. M. Loidl et al., Precision measurements of beta spectra using metallic magnetic calorimeters within the European metrology research project MetroBeta. J. Low Temp. Phys. **199**, 451 (2020). https://doi.org/10.1007/s10909-020-02398-2
6. H. Sogarwal, P. Shukla, Measurement of atmospheric muon angular distribution using a portable setup of liquid scintillator bars. J. Cosmol. Astropart. Phys. **07**, 011 (2022)
7. www.nist.gov/pml/xcom-photon-cross-sections-database
8. A batch of 20 meters of the cable was measured on the Paquito detector of the Ultra-Low Background Service (ULBS) of Canfranc Underground Laboratory during 39.26 days. No contamination was found; all limits were in the μBq/m range, except for ^{238}U with a limit of 3.9 mBq/m.