Low-background X-ray detection with Micromegas for axion research

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Abstract. We have studied low-background techniques in order to improve the background level for Micromegas detectors. These detectors are good candidates for rare event searches thanks to the low mass and the radiopurity of the materials used in the construction; moreover they have good discrimination capabilities. The motivation of these studies is the reduction of the background level in the CAST experiment where three of the four detectors operating currently are Micromegas of the microbulk type. The last result of the experience acquired in low-background techniques has been the reduction of the background level by a factor 4.5 for two detectors in the CAST experiment, corresponding to an improvement of a factor 2 in signal strength.

1. Axion searches: CAST and IAXO
Axions could be produced in the Sun via the Primakoff effect and can be detected in the laboratory as x-rays via the inverse process in a strong magnetic field. This is the so-called helioscope technique [1], employed by the CAST experiment and which will also be exploited in the future IAXO.

1.1. The CAST experiment
The CERN Axion Solar Telescope experiment [2] is looking for Axion Like Particles (ALPs) since 2002. Using a LHC prototype dipole magnet which provides a magnetic field of 9T and is pointing at the Sun two times per day (during sunrise and sunset) around 1.5 hours each side. The signal of axions will be an excess of counts during the tracking in the X-ray detectors situated at the end of the four magnet bores. Three of the four detectors installed currently at CAST are Micromegas of the microbulk type [3].

CAST finished in 2011 the research program which includes a vacuum phase [4] for axion masses up to \( m_a \leq 0.02 \) eV and a buffer gas phase [5] [6] to increase the sensitivity to higher axion masses \( 0.02 \geq m_a \leq 1 \) eV which was divided in two parts respectively with \(^4\)He and \(^3\)He as buffer gas. Currently CAST is revisiting \(^4\)He phase and will revisit vacuum phase obtaining
a better sensitivity than in previous data taking due to a further reduction of the background levels in the detectors. The originalities of CAST are the use of an X-ray telescope to increase the signal to background ratio, and the use of low-background techniques which will be described in section 2.

1.2. The International AXion Observatory
IAXO, the International Axion Observatory [7] [8], will improve CAST’s sensitivity by more than one order of magnitude. IAXO will exploit all the innovations of CAST with a larger toroidal magnet built for axion physics and all bores will be equipped with an X-ray telescope; moreover it will require low-background detectors. The Conceptual Design Report and a Letter of Intent for IAXO are under preparation.

2. Low-background techniques
CAST microbulk Micromegas exploit three different background strategies:

- **Low intrinsic radioactivity**: Micromegas detectors are intrinsically radiopure due to the low mass and clean materials that are used in the construction, mainly copper, Plexiglas and kapton. The radiopurity of these detectors has been measured in the Canfranc Underground Laboratory (LSC) by a germanium detector [10] obtaining excellent results.
- **Signal topology**: The axion signature will be an excess of X-ray in the energy range from 1 to 10 keV. This kind of events in our detectors are point-like events and daily calibrations with $^{55}$Fe source define the characteristic parameters of X-ray like events [9]. Micromegas detectors have two different readouts:
  - The pulse induced in the mesh, which gives time information and characteristic observables like **risetime, width, amplitude and integral**.
  - The charge collected in the strips of the anode, obtaining spatial resolution and defining **clusters** as a group of consecutive fired strips, allowing to define alternative observables in the strip plane like **cluster size, shape and charge**.
Finally the combination of the different parameters of the observables during the calibrations define selection criteria for the background events obtaining excellent discrimination capabilities.
- **Shielding**: It is made of different layers of materials: external lead shielding and inner copper. The shielding at CAST is continuously evolving and recently has been improved for two detectors at CAST. The upgrade includes an active muon veto which will be described in section 3.1.

2.1. Measurements at the LSC
A specific set-up to evaluate the different background sources is a replica of a CAST microbulk detector installed at the Canfranc Underground Laboratory (LSC). The LSC is situated at Canfranc (Huesca) in the Spanish Pyrenees with a depth of 2500 m.w.e. where the muon flux is reduced by a factor $10^4$ relative to surface. The set-up (Figure 1 left) is composed by a shielding of 10 cm of external lead and an inner copper layer with a thickness of 2.5 cm. Moreover nitrogen is flushed close to the detector to avoid Radon. In these conditions [11] [12] the background level is $< 2 \times 10^{-7} \text{ c keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$ in the $[2 - 7]$ keV range (Figure 1 right), 30 times lower than nominal CAST background $\sim 6 \times 10^{-6} \text{ c keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$ (before 2012 shielding upgrade).
2.2. Simulations

The motivation of the simulations is to reproduce the background level observed in the Micromegas detectors at CAST, where the environmental $\gamma'$s flux has been experimentally measured and used as input for the simulations. The complete CAST set-up geometry has been implemented in GEANT4 to simulate physical events like $^{55}$Fe calibration X-rays or environmental $\gamma'$s. Afterwards with RESTSoft, a code developed at the University of Zaragoza, the drift and the diffusion in the chamber is simulated using Magboltz for the gas parameters. Finally the electronic response of the detector is implemented. A comparison between simulated and experimental data is presented in Figure 2.

![Figure 2](image2.png)

**Figure 2.** Left: Comparison between a $^{55}$Fe calibration and a simulated one. Right: Background level in function of the shielding thickness for measurements at surface (blue dots), LSC (red dots) and simulations (green dots)

From the results shown on the right part of Figure 2 we conclude that the background level at surface has an important contribution of cosmic muons. This hypothesis has been confirmed by simulations, the background level versus the thickness of the shielding at the LSC (where muons are suppressed) can be reproduced by simulated data only using external $\gamma'$s as input. But this behaviour cannot be reproduced by the measurements at surface level due the contribution of cosmic muons. These results motivated the installation of a cosmic veto at CAST.
3. Background levels at CAST
The Micromegas detectors at CAST have reduced the background level by a factor $\sim 50$ from the beginning of the experiment, with several upgrades which include the detector design from classic Micromegas to bulk and microbulk technology, the shielding thickness and the analysis of the data. Two remarkable improvements in the background reduction were related with a shielding upgrade. In 2007 was the first installation of a shielding for the detectors, made by two layers of 25 mm of external lead shielding and 5 mm of inner copper improving the background 4.5 times (dots inside the green ellipse in Figure 3). In 2012 a shielding upgrade was made in the sunset detectors (blue dots in Figure 3) that will be detailed in next section.

3.1. Shielding upgrade of 2012
The shielding upgrade of 2012 for the Micromegas detectors at CAST in the sunset side is the result of the experience acquired in low-background techniques, the improvements includes:

- New shielding design made of 10 cm of external lead and 1 cm of inner copper. Now the shielding is more compact, improving the shielding around the pipes and magnet bores (Figure 4 left).
- The materials close to the detectors are radiopure (mainly copper and kapton) and have been carefully cleaned. Moreover all the steel pieces in the inner part of the shielding have been replaced by copper to prevent the $[5-7]$ keV fluorescence peaks.
- Active muon veto: As shown in section 2.2 muons have an important contribution at surface level and can induce fluorescence in the materials close to the detector. With this upgrade we obtained a 25% of background reduction in the $[2-7]$ keV energy range (Figure 4 right) with a non optimum veto (only 45% of coverage due to mechanical limitations), the veto coverage will we improved in next data taking campaigns.

![Figure 3. Evolution of the background level in Micromegas detectors at CAST (black and blue dots) and background level in special conditions at LSC (red dot)](image-url)
Figure 4. Left: Shielding upgrade for the Micromegas detectors of the sunset side in the CAST experiment. Right: Background spectra after the shielding upgrade before (red dots) and after the veto cut (blue triangles). It is remarkable the reduction of the fluorescence peak of the copper (8 keV) after the veto cut as a hint of the induced fluorescence by muons.

After the upgrade the background level reached was $\sim 1.5 \times 10^{-6} \text{ c keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$, a factor 4.5 of reduction in comparison with previous campaigns of data taking.

4. Future prospects
CAST will revisit the vacuum phase in 2013 and a new X-ray telescope will be installed in the sunrise Micromegas line, increasing the sensitivity of CAST due to the better signal-to-noise ratio. Also a new detector and shielding design has been proposed, motivated by the results obtained in the sunset upgrade and to improve the weak points of previous set-ups. In the new design the body and the support of the chamber is made completely of copper with a thickness of 2.5 cm also used as inner shielding; the window is smaller due the telescope and it will be tighter, the external shielding is made by 10 cm of lead and a cosmic scintillator will be installed. Another improvement is the new DAQ electronics, based on the AFTER chip [13] replacing the actual Gassiplex-based electronics [14] in all Micromegas detectors at CAST. In the AFTER-based electronics the strips pulses are digitized and the pulse shape analysis could be extended to every strip and a further background reduction could be achieved.

With the upgrades described previously CAST could improve the vacuum results down to a sensitivity of $g_{\alpha\gamma} < 5.9 - 6.3 \times 10^{-11} \text{ GeV}^{-1}$ (Figure 5) corresponding to a factor 4-5 in signal strength.

The long term prospects are focused on the International AXion Observatory. An ultra-low background Micromegas is required for IAXO, with the goal of a background level of $10^{-7} \text{ c keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ at surface level, down to $10^{-8} \text{ c keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ if possible. With a dedicated magnet, optics and ultra-low background detectors, IAXO could improve the sensitivity of CAST in a factor $\sim 18$ ($10^5$ in signal strength) [15]. Thanks to IAXO a big part of the QCD axion model could be explore next decade.

5. Conclusions and next steps
The work presented here is focused on reducing the background levels in Micromegas detectors and further developing low-background techniques. The goal is to build a background model for Micromegas detectors using all the information acquired with the measurements at the LSC and in the laboratory at surface level. The simulations are an important input to evaluate the different contributions in the final background of external $\gamma$'s, muons and the intrinsic radioactivity of the detector. The proposed upgrade for CAST in the Sunrise line will be
Figure 5. Expected sensitivity at CAST with the upgrades proposed for 9 months of data taking in vacuum. Two assumptions in the background for the Micromegas detectors have been computed a conservative scenario with a background level $1.5 \times 10^{-6} \text{ c keV}^{-1} \text{ cm}^{-2} \text{s}^{-1}$ (black line) corresponding to a sensitivity of $g_{a\gamma} < 6.34 \times 10^{-11} \text{ GeV}^{-1}$ and an optimistic scenario $8 \times 10^{-7} \text{ c keV}^{-1} \text{ cm}^{-2} \text{s}^{-1}$ (red line) with a sensitivity of $g_{a\gamma} < 5.94 \times 10^{-11} \text{ GeV}^{-1}$. Plot taken from [16].

important for the development of low-background techniques and it will be crucial in order to improve the background levels required for IAXO.

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