Axion Search and Research with Low Background Micromegas

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Helioscopes are one of the most promising techniques for axion discovery in which low background X-ray detectors are mandatory. We report the latest developments of the Micromegas detectors for the CERN Axion Solar Telescope (CAST). The use of low background techniques has led to background levels below 10^{-6} c keV^{-1} cm^{-2} s^{-1}, more than a factor 100 lower than the first generation of Micromegas detectors at CAST. The helioscope technique can be enhanced by the use of an X-ray focusing device, increasing the signal-to-background ratio. A new dedicated X-ray optic was installed at CAST during 2014 with a low background Micromegas in its focal plane. Apart from increasing CASTs sensitivity, the system has been conceived as a technological pathfinder for the International Axion Observatory IAXO.

1 Introduction

Axions and ALPs are well motivated particles that have been extensively searched since past decades, being the helioscope technique one of the most promising for axion discovery. The helioscope strategy was proposed by Sikivie [1] in 1983. Axions and ALPs could be produced in the Sun via Primakoff conversion. These solar axions could be reconverted into photons inside strong magnetic fields via inverse Primakoff effect. The expected axion signal would be an excess of X-rays in the detectors placed at the magnet bore ends while the magnet is pointing to the Sun and thus, low background X-ray detectors are mandatory.

Different helioscopes have been developed for axion searches, the most sensitive of which is the CERN Axion Solar Telescope (CAST), operating at CERN since 2003. One of the singularities of CAST is the use of X-ray telescopes in order to improve the signal to background ratio. Three of the four detectors currently installed at CAST are of the Micromegas type. Beyond CAST, a new generation helioscope has been proposed: IAXO the International AXion

Observatory [2]. IAXO will exploit the helioscope technique with a dedicated supertoroidal magnet, X-ray optics and ultra-low background detectors, improving CAST sensitivity by more than one order of magnitude.

2 Low background techniques

The Micromegas detectors installed at CAST have experimented a reduction of two order of magnitude in the background level since the beginning of the experiment. Different strategies have been developed in order to reduce the background of the detectors [3]: the intrinsic radiopurity of the Micromegas readout [4], the detector performance (closely related with the improvements on the manufacturing process), the event discrimination of the events (that could be improved by the upgrade of the front end electronics to the AFTER [5] chip) and, finally, the shielding, which is mainly composed by different copper and lead layers and an active muon veto. These techniques have been developed in the context of the TREX project [6] at the University of Zaragoza.

2.1 Test benches and simulations

The main purpose of the test benches and simulations are to determine the different contributions to the background. The measurements performed in special setups were crucial for the upgrade of the Micromegas detectors at CAST. Two different setups have been mounted: one underground at the Laboratorio Subterráneo de Canfranc (LSC) and other at surface level.

The setup at the LSC shows the lowest background level, $\sim 10^{-7}$ c keV^{-1} cm^{-2} s^{-1} [3], in an environment where the muon flux is reduced by a factor 10^4 relative to surface. Different contributions have been measured at Canfranc, like the aluminum cathode and the effect of the airborne ^{222}Rn. On the other hand, the measurements performed at surface level were important in order to determine the contribution the cosmic muons, for this purpose two plastic scintillators were installed as active muon vetoes. The background level after the discrimination of these events diminished to $\sim 10^{-6}$ c keV^{-1} cm^{-2} s^{-1} of which the scintillators account for a 50% of the background events.

In order to understand the experimental results different simulations have been performed, using the RESTSoft tools [7], developed by the group at the University of Zaragoza. The simulations have been extremely important when it came to the shielding upgrade of the Micromegas detectors at CAST. The results of these studies confirmed the importance of the cosmic muons to the contribution of the background level. Following, the lead shieldings were extended along the magnet bore pipes, in an attempt to lower the contribution of the cosmic events.

2.2 Micromegas at CAST: State of art

Following the prescriptions of the low-background studies, the Micromegas detectors at CAST were upgraded. In a first stage a new shielding design for the Micromegas at the sunset side was installed. The different lead and copper layers of the shielding have been increased and two plastic scintillators have been installed in order to minimize the effect of the cosmic muons. Also, the electronics have been upgraded to the AFTER chip. After these upgrades the background level was reduced to $\sim 10^{-6}$ c keV^{-1} cm^{-2} s^{-1} [8], a factor ~ 6 of reduction with respect to the previous set-up.

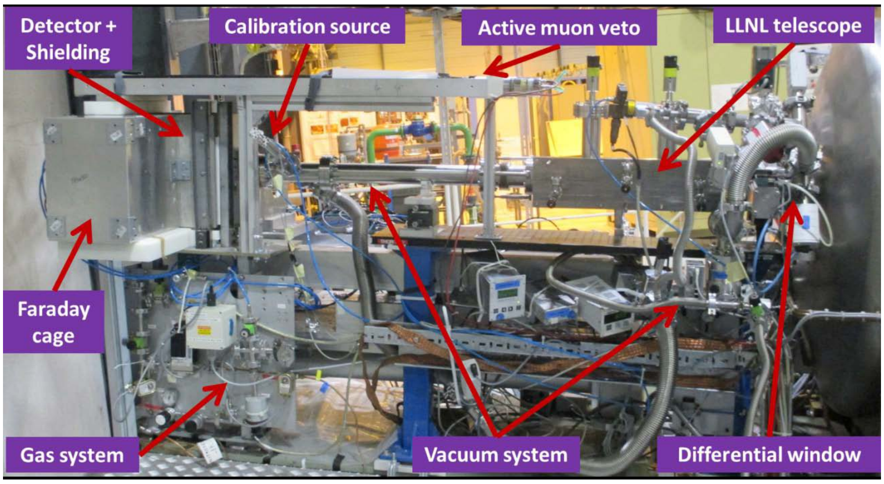

Figure 1: Photo of the new Sunrise Micromegas + X-ray telescope system in the CAST experiment. The different parts of the set-up have been labeled.

During 2014 a new X-ray focusing device was installed in the sunrise side with a Micromegas in its focal plane. It is the first time an X-ray optic is specifically designed and built for axion research. Moreover, the detector has a novel design that summarizes the current state of art on low background techniques developed for the Micromegas detectors.

The X-ray telescope has been manufactured using the same techniques developed for the NASA NuSTAR mission [9]. It consists of segmented glass substrates with 13 W/B_4C nested layers that lead to a focal length of 1.5 m and a focusing spot from 1–5 mm^2. The new X-ray telescope represents a big milestone for CAST, as it is expected to improve the effective background of the Micromegas by a factor ~ 100 and could be considered as a pathfinder for IAXO.

A new Micromegas detector has been designed and built for the sunrise side in which the body and the chamber of the detector is made of 18 mm thick radiopure copper. The materials close to the detector, mainly copper and polytetrafluoroethylene, are intrinsically radiopure and have been carefully cleaned. Also, a field shaper has been installed in order to ensure the uniformity of the drift field. The setup includes all the features of the sunset upgrade, like the shielding design, a plastic scintillator and the AFTER electronics (see Figure 1). In addition, new Micromegas detectors have been manufactured with excellent spatial and energy resolution. After the implementation of these upgrades the background was reduced to 8×10^{-7} c $keV^{-1}cm^{-2}s^{-1}$, the lowest level that have been reached by a detector at CAST.

The X-ray telescope and the Micromegas were installed and aligned in August 2014. The alignment procedure was performed with a laser which was properly aligned with the line and using a transparent chamber replica. The quantum efficiency of the Micromegas has been increased by the use of a new cathode design; now the signal spot is centered in the central circle of the detector avoiding the grid structure.

Due to the reduction of the background of the Micromegas and the new X-ray telescope, CAST will improve its previous limit in a re-scanned vacuum phase to an expected value of $g_{a\gamma} < 6 \times 10^{-11}$ GeV^{-1} as shown in Figure 2.

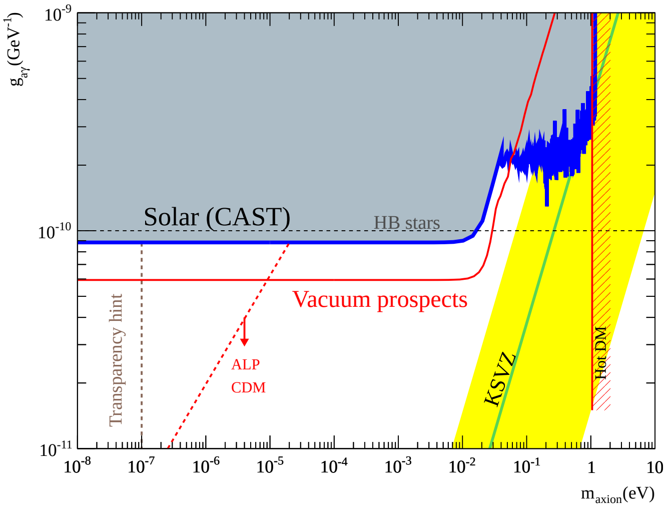

Figure 2: Expected sensitivity of the new vacuum phase in the CAST experiment (red line), in comparison with the current CAST limit (blue line). ALP hints and theoretical limits are also drawn.

3 Future prospects

Although the research in low background techniques in Micromegas detectors has led to an impressive reduction of the background at CAST, an ultra-low background detector is required for IAXO, with a goal of 10^{-7} c keV^{-1} cm^{-2} s^{-1}, down to 10^{-8} if possible. New improvements and research lines have been proposed for IAXO such as: veto coverage, extended scintillator surface area, and the use of new gas mixtures like Xe or depleted Ar in order to remove the ^{39}Ar isotope. Thanks to IAXO, a big part of the parameter space could be explored during the next decade, with a sensitivity that will enter in the most favored regions for axions and ALPs.

IAXO could also be sensitive to non-hadronic Solar axions, with a flux that could be considerably larger than the Primakoff conversion [10]. Also, more exotic particles could be explored at IAXO like chameleons. In both cases the key would be the reduction of the low energy threshold and the increase of the transparency of the detectors to soft X-rays. New research and design lines are being investigated:

- New thin windows: The efficiency of the Micromegas at low energies is limited by the X-ray transparency of the cathode window. Different materials are being investigated.
- AGET front-end electronics: The novel AGET [11] electronics keep the main features of the AFTER but with auto-trigger functionality. So a lower energy threshold could be archieved.
- Resistive Micromegas: The use of this type of detectors will allow to work at higher gain.

4 Conclusions

Axions and ALPs are well motivated particles that appear as a solution of the strong CP problem, being attractive candidates to form part of the dark matter. The CAST experiment has been looking for solar axions since 2003 being the most sensitive helioscope so far. The helioscope technique could be enhanced, among other things, by reducing the background of the detectors, with this purpose different strategies have been developed and have led to a background reduction of a factor ~ 100 at CAST.

The new X-ray telescope and the low background Micromegas system at CAST will improve the sensitivity of the experiment and could be considered as a pathfinder of the new generation axion helioscope IAXO. New research lines have been proposed in order to reduce the background level of the Micromegas that are required for IAXO. On the other hand, the reduction of the low energy threshold in the Micromegas will open new physics for IAXO.

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