An ultra-low-background detector for axion searches

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Abstract. A low background Micromegas detector has been operating in the CAST experiment at CERN for the search of solar axions since the start of data taking in 2002. The detector, made out of low radioactivity materials, operated efficiently and achieved a very low level of background (5×10\textsuperscript{-5} keV\textsuperscript{-1} cm\textsuperscript{-2} s\textsuperscript{-1}) without any shielding. New manufacturing techniques (Bulk/Microbulk) have led to further improvement of the characteristics of the detector such as uniformity, stability and energy resolution. These characteristics, the implementation of passive shielding and the improvement of the analysis algorithms have dramatically reduced the background level (2×10\textsuperscript{-7} keV\textsuperscript{-1} cm\textsuperscript{-2} s\textsuperscript{-1}), improving thus the overall sensitivity of the experiment and opening new possibilities for future searches.

1. Introduction
The CAST (CERN Axion Solar Telescope) experiment is using a decommissioned LHC dipole magnet to convert solar axions into detectable X-ray photons. Axions are light pseudoscalar particles that arise in the context of the Peccei-Quinn [1] solution to the strong CP problem and can be Dark Matter candidates [2]. Stars could produce axions via the Primakoff conversion of the plasma photons. The CAST experiment is pointing at our closest star, the Sun, aiming to detect solar axions. The detection principle is based on the coupling of an incoming axion to a virtual photon provided by the transverse field of an intense dipole magnet, being transformed into a real, detectable photon that carries the energy and the momentum of the original axion. The axion to photon conversion probability is proportional to the square of the transverse field of the magnet and to the active length of the magnet. Using an LHC magnet (9 T and 9.26 m long) improves the sensitivity by a factor 100 compared to previous experiments. The CAST experiment has been taking data since 2003 providing the most restrictive limits on the axion-photon coupling [3]-[6] for masses m_a < 0.02 eV. At this mass the sensitivity is degraded due to coherence loss. In order to restore coherence, the magnet can be filled with a buffer gas providing an effective mass to the photon [4]. By changing the density of the buffer gas in steps, one can scan a wide range of axion mass values. At the end of 2005 CAST started such a program, entering its phase II by filling the magnet bore with He gas. From 2005 to 2007, the magnet bore was filled with \textsuperscript{4}He gas extending the sensitivity to masses up to 0.4 eV [7]. From March
2008 onwards the magnet bore has been filled with $^3$He and the sensitivity should be increased up to $m_a < 1.2\ eV$ by the end of the $^3$He run in 2010.

The CAST experiment has used three different types of detectors to detect the X-rays originated from the conversion of the axions inside the magnet: a Time Projection Chamber [7], an X-ray telescope [9], and a Micromegas detector [10]. The Micromegas detector of CAST is a gaseous detector optimized for the detection of low energy (1–10 keV) X-ray photons. It is based on the micropattern detector technology of Micromegas (MICROMEsh GAseous Structure) developed in the mid 90’s [11]-[13]. The advantages of using Micromegas for such low-threshold, low-background measurements as required by the CAST experiment, include sensitivity at the keV and sub keV energy region where very good energy resolution can be achieved, excellent spatial resolution, one dimensional or X-Y readout capability, stability, construction simplicity and low cost. In addition it allows flexibility in the construction materials, the proper choice of which would lead to a detector appropriate for low background measurements.

2. The Micromegas detector in CAST

During CAST phase I and $^4$He data taking periods, a conventional Micromegas was used [10], covering one of the 4 magnet bore exits. Thought it was the only detector without any shielding it showed the lowest background level of $-5\times10^5\ \text{keV}^{-1}\cdot\text{cm}^2\cdot\text{s}^{-1}$ of all 3 detectors used. Due to this fact and, in combination with the development of new manufacturing techniques (Bulk & Microbulk, [14]), the existing Micromegas and TPC were replaced with three new Micromegas detectors for the $^3$He phase. The compact design of the new detectors allowed the implementation of passive shielding, which further reduced the background by a factor ~3, reaching the level of $\sim1\times10^5\ \text{keV}^{-1}\cdot\text{cm}^2\cdot\text{s}^{-1}$ [15] during April – September 2008 data taking period.

In the following cryogenic maintenance intervention two of these detectors were replaced by newer Microbulk type models. These detectors are expected to have a very low intrinsic background since they are made of low radioactivity materials: kapton and copper for the detector and Plexiglas and aluminium for the chamber. Radiopurity measurements of several detectors parts are being done in the Canfranc Underground Laboratory, and are used to continuously improve the intrinsic radioactivity of new series of detectors and to build a full simulation model for the detector background that will certainly be of great use to study the experimental results presented in this paper.

2.1. Background reduction

The data acquisition system used in CAST Micromegas is registering the analogue signal from the mesh with 1 GHz FADC and the integrated charge on each strip using Gasiplex cards [10]. From this information several parameters can be extracted, that characterize the interaction of particles with the detector gas, like risetime and pulse duration from the analogue signal and hit multiplicities from the strip data. An X-ray of energy less than 10 keV would cause primary ionization localized in a range less than 1 mm. This would give a narrow pulse with a fixed risetime determined by the detector characteristics, and a mean strip multiplicity which corresponds to ~5 mm. A minimum ionizing particle like cosmic muons would cause spatially extended ionization resulting to broader pulses and higher multiplicities (Figure 1).

The raw trigger rate of the Micromegas detectors in CAST is of the order of 1 Hz. Most of these events concern muons and can be rejected in the offline analysis with the proper particle recognition algorithm. The aim of such algorithms is to reject all signals that are not compatible with X-rays, but maintaining most of the X-ray compatible ones. The data reduction factor has reached the level of $10^{-3}$, while maintaining 80% of the 6 keV X-rays from $^{55}$Fe calibration runs. The low level of the non shielded Micromegas detector used in phase I has been achieved by only this data reduction.

2.2. Detector shielding

Environmental gamma rays and neutrons could cause X-ray compatible signals in the detector via Compton and elastic scattering respectively. If the deposited energy in the gas is of the order of few
keV the signal will have characteristics similar to the X-rays and can not be rejected offline. These signals can be only reduced by the implementation of proper shielding.

Figure 1. Up-left: correlation of mesh pulse characteristics for a calibration run with 6 keV X-rays from $^{55}$Fe. Up-right: the same parameters for a data (cosmics) run. Down left: strip multiplicities for a calibration run. Down right: strip multiplicities for a data run. By applying appropriate cuts the cosmic data can be reduced by a factor of $\sim 10^{-3}$, while the X-rays are reduced only by $\sim 20\%$.

The shielding that was adopted for the Micromegas detectors consists of an inner archeological Pb layer 3-5 cm thick, and an external polyethylene layer 15-20 cm thick. In-between a Cd foil is placed in order to absorb the neutrons which have been thermalized in the polyethylene. A 5 mm Cu layer is placed inside the lead serving also as faraday cage. The whole shielding must be made air-tight and is flushed with nitrogen in order to remove Radon. Studies done in the CAST experimental area have shown that such shielding results to a background reduction of a factor more than 3 (Figure 2).

Figure 2. Left: pictures of the CAST sunrise Micromegas shielding. In the ideal case the detector should be covered by all shielding elements in a $4\pi$ geometry. However this was not possible due to space limitations and detector electronics. Right: results from the background reduction tests. A reduction more than 3 is observed in the 1-7 keV energy range which was used for the limit calculation in phase I. This reduction is bigger in higher energies.
3. The “Ultra-low-background” case

3.1. The measurements

Special care was taken for the shield air-tightness during the installation of the new detectors in October 2008. Since then, the detector was taking data in stable conditions for a period over than one month. $^{55}$Fe calibration runs were taken regularly (~daily) at random times during the day, in order to check the gain and software cuts stability. The source was placed in a pneumatic mechanism that could move it inside the CAST vacuum tube in front of the Micromegas window at a distance of 1m, thus simulating X-rays that would emanate from the axion to photon conversions in the 9T magnetic field. These runs have shown a stable detector performance (Figure 3).

Figure 3. $^{55}$Fe calibration runs during Oct-Nov 2009. The gain stability is shown on the left plot, and the software efficiency on the middle one. The right plot is showing the x-y image of the calibration runs in the area of expected signals. The image of the drift window strongback is clearly visible, while no serious defect is seen in the whole detector area.

The background level of this detector was initially similar to the one of the previous detectors used at the same place with similar shielding, but it appeared to decrease with time (Figure 4). The decrease rate was compatible with Radon's decay time, which could be an indication that the observed background was dominated by Radon radioactivity. This reduction stopped on the 4th of November and the background level returned to the initial values. It was found later that the moment of the increase coincided (within an hour) with an intervention on the nitrogen central supply line which caused interruption of the shielding nitrogen flushing.

Figure 4. Left: background level evolution with time; the sudden increase on the 4/11 coincided with an interruption of the nitrogen flushing. Right: evolution of the analogue spectrum; the three spectra correspond to the data of first few days (blue), the second week (red) and the last two weeks of (black).

The background rate started decreasing again after the interruption and a week later reached a surprisingly low level of the order of $2 \times 10^{-7}$ keV$^{-1}$·cm$^{-2}$·s$^{-1}$. It remained at this level until the 27th of
November when a series of power cuts lead to the end of the run. During this period of two weeks the background level of data runs was stable at this very low level, while no defect has been observed in the calibration runs.

3.2. Discussion
Several considerations about this data taking period allow us to exclude that the observed ultra-low-background is due to a detector malfunction or an artefact.

The $^{55}\text{Fe}$ calibration runs taken during this period show that the detector response to 6 keV X-rays remained practically unchanged, as shown in Figure 3, while the reduction is observed for that energy as well (Figure 4). Furthermore, the fact that the calibrations were taken at random moments during the day exclude possible diurnal effects.

No hardware problems that would imply detection defects like increased deadtime have been observed. A characteristic example of a long run is presented in Figure 5, where the detector trigger rate appears to be stable in the nominal value (0.7 Hz) during 3 days, while only 5 events remain after the software cuts. Similar behavior was observed in the (shortest) runs of this period as well.

The analogue spectrum after cuts seems to remain unchanged in shape and it only scales down with time (Figure 4). This fact is compatible with the assumption that most of the observed counts are fluorescence X-rays caused by external radiation. Since the shielding is stopping most of the environmental gammas and the detector consists of low radioactivity materials the only remaining source of external radiation is radon trapped inside the shielding. In this case the lines of detector’s and shielding copper (8 keV), tube’s stainless steel iron (6 keV) and window’s aluminum (1.5 keV) would be excited and the accompanying argon escape lines ($E_x$-3keV) would also appear. The intensity of these lines should decrease with time if the shielding is air-tight. This kind of behavior is observed in Figure 4.

The radon scenario is also supported by the interruption of the nitrogen flushing and the simultaneous increase of the background rate.

Further analysis of data taken during this period has revealed another characteristic of the detector’s behavior. Though the X-ray pulse parameters remained unchanged during the whole period, some of the parameters of the cosmic runs are changing, especially during the ultra low background period. This fact leads to the conclusion that the assumed “radon effect” could be observed in combination with an enhanced particle recognition efficiency. The reason of such behavior is currently under investigation with several detectors and configurations.

Similar behavior has been observed with the second detector as well, which was installed for testing at the same shielding for approximately 10 days during the shutdown. In this period the count rate dropped exponentially from the initial 2 to 0.3 counts per hour.
4. Conclusions

Rare event detection experiments, such as search for solar axions with CAST, demand stable and low background detectors. These demands are met by the Micromegas detector which can be constructed from low radioactivity materials and has properties that allow high background rejection efficiency. Such detectors have been used in CAST through all data taking campaigns. The implementation of passive shielding has enhanced the performance of these detectors, meeting the needs of CAST phase II, which demands a background level of the order of zero counts per hour. The recently developed Microbulk Micromegas lead to further reduced background levels. Its enhanced performance, that would imply 0.05 expected background counts per hour in the axion expected signal energy region, has been verified during on site test measurements.

The observed ultra-low-background level not only simplifies the CAST $^3$He data taking phase, but also opens new opportunities for future improvements. As an example can be noted the phase I result, which represents the strongest experimental bound in axion coupling constant [3]. This result has been dominated by the X-ray telescope [9], which showed a background rate of 0.15 counts per hour. Repeating these measurements using three new Micromegas detectors in parallel with the telescope, would lead to an improvement of the coupling constant limit by almost a factor of two, probing for the first time the axion parameter space well beyond astrophysical bounds [18].

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