Micromegas for Axion Search and Prospects

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Abstract. The Micromegas technology can be used to construct very powerful detectors for low background, low energy measurements. A Micromegas X-ray detector has been used to search for solar axions in the CAST experiment at CERN. The detector has an active area of 7cm x 7cm, a very good x-y position, and a good energy resolution. It is built using low radioactivity materials and it is capable of low energy X-ray measurements of a few hundred eV. Despite the lack of external shielding the obtained background level is below 5x10\textsuperscript{-5} counts/keV/cm\textsuperscript{2}/s. The detector is being upgraded with a reduced active area Micromegas module, a focusing X-Ray telescope and shielding, which are expected to further reduce the background by about two orders of magnitude.

1. Introduction
One of the long standing questions of Particle Physics is the so called ‘Strong CP problem’ [1-4] involving the non observation of CP violation in the strong interactions. The preferred resolution of this problem is related to the possible existence of a neutral pseudoscalar particle known as axion [5-7]. The original PQWW (Peccei-Quinn-Weinberg-Wilczek) axion was tied to the electroweak scale, with appreciable couplings to matter and large mass, and it was subsequently ruled out by experiment. Later models, such as the DFSZ [8-9] and KSVZ models [10-11], introduced the invisible axion, thus called due to its much weaker couplings and its tiny mass. The detection of this type of axion is based on its coupling to two photons, via the reverse Primakoff effect, and many experiments have tried to discover it, unsuccessfully so far. The axion, if it exists, should be rather abundant in the universe, a fact that makes it a very good cold dark matter candidate.

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CAST (the CERN Axion Solar Telescope) is the most recent high sensitivity experiment of the Helioscope type, which, since 2003, is searching for solar axions and is putting more strict limits on the axion coupling to photons [12-13]. CAST’s central instrument is a 9 Tesla, 10 meter long decommissioned prototype LHC superconducting magnet, which is mounted on a rotating platform and tracks the sun for about 3 hours per day. The axions created in the sun’s core can convert in the transverse magnetic field into equal energy X-ray photons to be detected by appropriate X-ray detectors mounted at the two ends of the magnet bores. Given the expected energy range of axions from the sun (1-10 keV), three types of detectors are being used in CAST: Micromegas, TPC and CCD (with a focusing telescope).

The CAST experiment was designed to be conducted in two phases. During the first phase, which was concluded by the end of 2004, the axion search was limited to very low mass axions (below 0.02 eV). The second phase started in 2005 and involves higher masses up to about 0.8 eV. Figure 1 shows the CAST experimental setup.

We will focus here in the description of the operating principle and some construction and performance details of the Micromegas detector as an axion probe in particular and as a low background, low energy X-ray measuring device for rare event detection in general.

2. The Micromegas X-ray detector
The principle of operation of the CAST Micromegas detector [14-16] is shown in figure 2. It is a gaseous detector and the X-ray detection is based on the photoelectric phenomenon. The detector housing is constructed from low natural radioactivity Plexiglas. The conversion drift region is 25 mm thick and is formed between a 4 µm thick aluminized polypropylene window glued on stainless steel strong-back and the

Figure 1: View of the axion search experiment CAST at CERN. The Micromegas detector and the CCD detector with an X-ray focusing telescope are located at the right end of the magnet whereas the TPC detector is found at the left end.

Figure 2: The CAST Micromegas detector principle.
micromesh plane. Ionization electrons are created along the short track of the photoelectron through an Argon–Isobutane (95%-5%) mixture at atmospheric pressure. These electrons are subsequently driven by the drift field (~0.5 kV/cm) into a high field multiplication region, a 50 micron thick space between the micromesh and the readout plane, multiply through an avalanche process and get collected by the readout strips. The field configuration around the micromesh holes is such that almost 100% of the drift electrons funnel through them and reach the high field region. At the same time, due to diffusion, most of the ions are collected by the mesh electrode. The micromesh signal is used to trigger the acquisition of an event. The charge collection plane consists of 192 X and 192 Y strips with a 350 µm pitch, an active area of 7 cm x 7 cm. The charge on the X or Y strips is read out with the help of electronic cards based on the Gassiplex chip [17] controlled by a CAEN sequencer with two CRAM modules in a VME crate. An X-ray photon, coming from the direction of the magnet, forms a charge cluster with a lateral size of, in average, 6 X and 6 Y strips.

Additionally the mesh signal of this Micromegas detector is recorded via a fast digitizer and it is used to reject signals without the expected shape. The digitizer card (MATACQ) is a 4-channel VME module [18], based on the MATRICE chip. It operates with up to 2 GHz sampling frequency.

The initial tests of the Micromegas were done at the PANTER X-ray facility of the MPI in Munich, using an X-ray Optics focusing device in front. These tests provided the working parameters of the Micromegas detector for the CAST experiment and proved the great capabilities of this technology in the domain of rare event searches. They also established the excellent energy resolution, position resolution, stability, linearity and robustness of the detector. In particular low energy X-rays, down to 600 eV, were able to be measured but with reduced efficiency due to the 1.5 micron Mylar window used at that time (Figure 4a,b). The situation can be improved with the use of thinner polypropylene windows (Figure 4c) and lower X-ray energies can be reached.
The Micromegas detector has been in stable operation, in the CAST experiment, since October 2002. The calibration is performed daily using an automated system with an $^{55}$Fe source placed externally close to the back of the detector. The gain stability has been measured to be less than 2% over long periods of time, for constant conditions. The detector is measuring background events at all times and mixed background and signal events during the solar tracking period (1.5 hours per day). The background comes from the natural radioactivity of the surrounding materials and the cosmic rays. The analysis of the events is based on the micromesh pulse shape and the topology of the cluster on the strips. It seeks the removal of events which are not events induced by X-rays coming along the magnet. The desired properties of such events are established by the analysis of the calibration data. At the end the residual background rate outside tracking is established and compared with the one during tracking. If there is an excess it will be attributed to axions from the sun [19]. The sensitivity of this methodology depends on how low is the residual background. Indeed, another remarkable feature of this detector is that it is able to reach a background rate of under $3 \times 10^{-5}$ keV$^{-1}$ cm$^{-2}$ s$^{-1}$. Figure 5 shows the background, for a certain detector configuration during 2004, before and after filtering. The peaks in the plot correspond to the photo peaks and the escape peaks of the various materials present in the detector. These peaks are clearly invisible in the raw data.

Figure 5: Raw data spectrum (histogram) compared to data after filtering (points).

3. The new Micromegas X-ray detector line

While the second phase of the CAST experiment is ongoing, the Micromegas X-ray detector line is being redesigned to further increase the sensitivity to axions by further decreasing the residual background by 2 orders of magnitude. The new features include the design and use of a new, smaller in effective area, detector with a novel X-ray focusing telescope and shielding, as seen in figure 6.

To improve the efficiency, the new Micromegas design includes a more transparent X-ray window and the use of heavier gas (Xe based mixture). To
improve the background cleaner materials are used and the mesh and strips are golden plated to avoid the copper fluorescence. Also a new design of the mesh support has improved the energy resolution further. The calibration is also improved since the sources will be located in the magnet line and the photons do not have to traverse any different material as compared to axion generated X-ray photons. Figure 7 shows the new design of the Micromegas detector.

Figure 7: The new Micromegas detector for CAST. The same X-Y strip structure as before is maintained.

The new X-ray focusing optic is developed specifically for CAST and involves a new manufacturing method using plastic substrates. It is composed by 14 nested conical shells, with an inner surface Iridium coating of about 30 nm. The focal length is 1.3 m and the spot size is of the order of 2 mm square, which corresponds to a reduction of the background by ~100 as compared with the detector without X-ray focusing (see Figure 8).

The smaller size of the new Micromegas allows the addition of external shielding to protect the detector from the radioactivity of surrounding materials as well from the presence of radon gas in the area (see Figure 9). Radiation free materials will be used in the construction of the shielding. This is expected to further reduce by a factor of 4 the background expected.

The new Micromegas line (the detector without the shielding and a first version of the focusing optics) was tested at the PANTER X-ray facility. However, the efficiency of the optics was lower than expected. Subsequently the necessary corrections in the manufacturing process and materials were
determined and a second focusing module is under construction and expected to meet the specifications. When this optics module is ready, the tests will be repeated and the final setup will be implemented in the CAST experimental apparatus immediately after that.

4. Conclusions

The CAST Micromegas detector has been taking data for the axion searches since 2003. It had a very good performance in terms of position resolution, energy resolution, very low energy measurement capability, efficiency, linearity, background rejection and presented a remarkable stability. Micromegas is being upgraded for the second phase of the CAST experiment with further improvement in the efficiency, the energy resolution and the background rejection. An X-ray Optics is under construction, which in conjunction with the Micromegas detector will increase the signal to background ratio by about two orders of magnitude. All these remarkable features make this detector a powerful tool for the axion and other rare event searches.

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