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Imaging in (high pressure) Micromegas TPC detectors

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Abstract: The T-REX project of the group of the University of Zaragoza includes a number of R&D and prototyping activities to explore the applicability of gaseous Time Projection Chambers (TPCs) with Micromesh Gas Structures (Micromegas) in rare event searches where the pattern recognition of the signal is crucial for background discrimination. In the CAST experiment (CERN Axion Solar Telescope) a background level as low as 0.8×10^{-6} counts keV^{-1} cm^{-2} s^{-1} was achieved. Prototyping and simulations promise a 10^5 better signal–to–noise ratio than CAST for the future IAXO (International Axion Observatory) using x-ray telescopes. A new strategy is also explored in the search of WIMPS based on high gas pressure: the TREX-DM experiment, a low energy threshold detector. In both cases, axion and WIMP searches, the image of the expected signal is quite simple: a *one cluster* deposition coming from the magnet bore in the case of axions and, if possible, with a *tadpole* form in the case of WIMPs. It is the case of double beta decay (DBD) where *imaging* and *pattern recognition* plays a major role. Results obtained in Xe + trimethylamine (TMA) mixtures points to a reduction in electron diffusion which improves the quality of the topological pattern, with a positive impact on the discrimination capability, as shown in TREX-$\beta\beta$ prototype. Microbulk Micromegas are able to image the DBD ionization signature with high quality while, at the same time, measuring its energy deposition with a resolution of at least a $\sim$ 3% FWHM at the transition energy $Q_{\beta\beta}$ and even better (up to$\sim$ 1% FWHM) as extrapolated from low energy events. That makes Micromegas-based HPXe TPC a very competitive technique for the next generation DBD experiments (as PANDAX-III). Here, it will be shown the last results of the TREX project detectors and software concerning Axions, Dark matter and double beta decay.

Keywords: Gaseous detectors, Micropattern gaseous detectors (MicroMegas), Gaseous imaging and tracking, Dark Matter detectors, Double-beta decay detectors

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Contents

1 T-REX Project (TPCs for Rare Event eXperiments)

Gaseous Time Projection Chambers offer high potential for event recognition through signal topology in gas, precisely registered by a patterned readout. A spatial resolution of the order of micrometres is reachable using high granularity readouts and dedicated software tools, working at high pressure increases the detector efficiency, and the relative large choice of target species allows to find the most suitable gas mixture for any application and optimize some crucial detector parameters as drift velocity or diffusion which have a direct impact on energy and spatial resolutions.

The development in the last decades of novel readout techniques based on micropattern gas detectors (MPGD) simpler, more robust and mechanically more precise, together with advances in electronics, in size, density and cost, with the bonuses of the good scalability prospects, have placed this technology in an excellent position to be used in many applications.

These modern TPCs, which can be built using radiopure materials, seem perfect for rare event detection. Both, the radiopurity and the possibility of event discrimination, are essential in the search for these phenomena of extremely low probability of occurrence hidden under much higher levels of natural radioactivity events. Pioneer experiments as Gotthard for double beta decay (DBD), DRIFT for dark matter WIMP searches or CAST in its search for solar axions have explored this line.

Since 2009, the ERC-funded T-REX project has been carrying out exploratory R&D and small scale prototyping where recent developments in MPGDs (=Micromegas) and low background expertise have been merged to probe the feasibility and competitiveness of the technology [1][2]. The R&D has reviewed aspects like the radiopurity of novel MPGD fabrication techniques or that of closely-related components, the development of software and discrimination algorithms, the characterization and measurements of experimental parameters of interest, and, finally, the realization of demonstrative prototypes at the scale necessary to assess the merit of the technique to be used in the next generation of *rare event* searches.

In the following we will report on the expertise acquired by our group in the use of MicroMegas-based TPC for rare event searches: from the pioneering detectors in the successful CAST experiment for axion searches to recent high pressure TREX-DB and TREX-DM prototypes. We will focus on the *imaging* performance of the detectors.

2 Axion searches: x-ray detection with Micromegas

The most powerful axion helioscope so far, the CERN Axion Solar Telescope (CAST) [3], uses a Large Hadron Collider (LHC) dipole prototype magnet (9 T over a length of 9.3 m and an aperture of $2 \times 15\,\mathrm{cm}^2$) to follow the Sun for 3 hours per day. In such a magnetic field solar axions are converted into x-rays whose typical energy distribution lies at the 1–10 keV range, with a peak at 4 keV. After more than a decade of operation, CAST has derived the most stringent experimental upper limits on the photon-axion coupling $g_{a\gamma}$, at the level of $10^{10}\,\mathrm{GeV}^{-1}$ for axion masses up to 1 eV. The International Axion Observatory has been proposed as a new generation of axion helioscopes: a large aperture superconducting magnet, an extensive use of x-ray focusing optics and low background x-ray detection techniques.

Micromegas detectors have been used in CAST since an early stage of the experiment for the detection of low energy x-rays. Typically, these detectors consist of a small TPC of around 3 cm height, filled with 1.4 bar Argon-2% isobutane mixture. X-rays coming from the magnet bore enter the conversion volume via a gas-tight window made of 4 μm aluminized mylar foil which serves as the cathode of the TPC and is supported by a metallic strong-back. The ionization charges produced by photon interactions in the gas volume are drifted and projected onto a $60 \times 60\,\mathrm{mm}^2$ Micromegas readout plane at the anode, where signal amplification and charge collection takes place. A fine pixelization with a typical pitch of 0.5 mm allows to get a clear image of any signal event candidate: point-like events inside a fiducial area. The use of an x-ray telescope reduces this fiducial area from the $14.55\,\mathrm{cm}^2$ projection of the magnet's circular bore to a small spot inside a ~ 8.5 mm diameter circle [4] (figure 1).

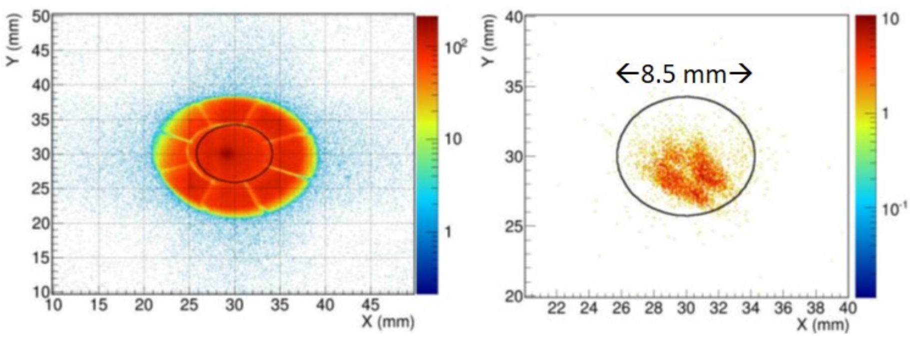

Figure 1. Effect of the x-ray telescope (right) on a ^{55}Fe calibration through the web-like window.

Continuous R&D works have progressively improved the detector performance up to the best background levels ever achieved [5]: around 10^{-6} counts keV^{-1} cm^{-2} s^{-1} in the [2–7] keV energy range at CAST site in CERN and values as low as 10^{-7} counts keV^{-1} cm^{-2} s^{-1} at the Laboratorio Subterráneo de Canfranc (LSC), suggesting that most of the background has a cosmic origin.

Three points have been the basis for the development carried out within T-REX in the framework of CAST experiment and as a benchmark for the future IAXO [6] (see [2] for more details):

1. Radiopurity. All materials have been screened with a low radioactivity: Microbulk Micromegas readouts are made out of just kapton and copper with very high standards of radiopurity. Signals can be extracted out of the detector to the front-end electronics, placed far and shielded from the detector.

2. Imaging. The fine 3D readout pattern and the relative z information from time of arrival are used to get a detailed image of the ionization signature in gas. Advanced software algorithms which include charge distribution and event topology have been developed for discrimination.

3. Shielding. An appropriate passive and active shielding surrounds the detectors.

Due to these results CAST-like Microbulk Micromegas are one of the detection technologies candidates to be used in IAXO. This next-generation axion helioscope, able to track the sun 12 hours per day, proposes the construction of a large superconducting 8-coil 20 m long toroidal magnet optimized for axion research. Its 60 cm diameter bores will be equipped with x-ray optics focusing the signal photons into 0.2 cm^2 spots to be imaged by ultra-low background x-ray detectors. About 4–5 orders of magnitude more sensitive to solar axions than CAST, IAXO will reach $g_{a\gamma}$ values of 10^{-12} GeV^{-1} for axion masses up to 0.25 eV.

A prototype detector has been built and will be run in the next months at the University of Zaragoza as part of the work for the IAXO Technical Design Report. The demonstrator and its shielding have been designed to prove experimentally the cosmic origin of the main component of the background; runs with Ar-based mixtures depleted from the ^{39}Ar isotope (a β emitter) or even a Xe-based mixture are foreseen to study a reduction in the intrinsic radioactivity; and an AGET-based front-end electronics which would allow an energy threshold below 400 eV, increasing the IAXO sensitivity to additional solar axion and axion-like particle emission channels, will be tested.

3 High pressure gas TPC for ^{136}Xe neutrinoless double beta searches

The observation of the neutrinoless double beta ($0\nu\beta\beta$) process would confirm the Majorana nature of the neutrinos, determine their effective mass, and provide information on the absolute mass scale and their mass hierarchy (normal or inverted). Though the two neutrino mode ($2\nu\beta\beta$) is a process already measured for eleven isotopes, the $0\nu\beta\beta$ mode remains unobserved. This is a very rare event and current limits on the decay half-period $T_{1/2}^{0\nu\beta\beta}$ are around 10^{23}–10^{25} years depending on the isotope, exploring values of the effective mass $m_{\beta\beta}$ of 0.2–0.4 eV.

The simplified figure of merit for DBD searches,

$$T_{1/2}^{0\nu\beta\beta} \sim \frac{a\epsilon}{A}\sqrt{\frac{Mt}{b\triangle E}} \tag{3.1}$$

where a is the isotopic abundance, ϵ the detection efficiency, A the atomic mass, M the target mass, t the exposure time, b the background level, and $\triangle E$ the energy resolution, points out the focuses for the experimental efforts. An exposure of the order of ton-years isotope and almost zero background in the region of interest (ROI) are needed to reach $m_{\beta\beta}$ sensitivities of a few meV and explore the inverted neutrino mass hierarchy region, the next milestone for DBD. This extremely low background will only be achieved using the most radiopure materials in detector construction and pattern recognition techniques to identify and discriminate events.

Though experimental considerations dominate the isotope choice and the observation in different isotopes will be highly advisable, xenon is one of the preferred option for leading experiments. Current limits on neutrinoless DBD come from EXO (liquid Xe TPC) and KamLAND-Zen (Xe diluted in liquid scintillator) last results.

A gas xenon TPC not only improves one order of magnitude LXe detector energy resolution, but, with appropriate readout granularity, its background rejection capabilities are a leap beyond any other detector. The two electrons of a $0\nu\beta\beta$ would imprint a clear signature: a long track with two high energy deposits (blobs) at both ends, homogeneously distributed in the gas volume, while background events coming mainly form ^{208}Tl and ^{214}Bi would produce multi track events or single track events but with just one end with a blob and, occasionally, beta electrons from walls touching the fiducial volume (figure 2). However, in the case of signal, x-rays produced in ionization and bremsstrahlung may escape from the TPC or produce secondary tracks or one of the electrons is emitted with very few energy to produce a blob. Also, for background events, extra (Compton or bremsstrahlung) secondary deposits of energy can produce another blob and the event can mimic a $0\nu\beta\beta$ signal. Pattern recognition is crucial for next generation DBD experiments for background reduction but also for unambiguous identification of a possible signal. The T-REX project [1] has

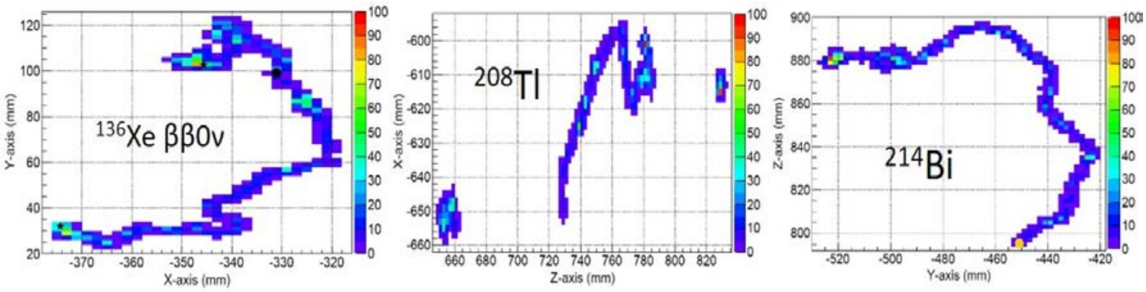

Figure 2. 2D images of simulated events (2×2 pixelated readout). It can observed the one–track–with–two–blobs pattern of ^{136}Xe DBD while ^{208}Tl is multitrack and ^{214}Bi gamma emission shows just one blob.

revamped, in the form of Micromegas-based HPXe TPC, the pioneering concept of topological identification in gas proposed by the Gothard experiment in the 90's. These ideas were also the seed for the NEXT experiment [7], now at the stage of prototyping with a 10 kg gas Xe TPC already installed in the Laboratorio Subterráneo de Canfranc (LSC) and whose final aim is to run a ~100 kg TPC. NEXT has finally focused on electroluminiscence signal and photon detectors. The T-REX works are in the base of the recent PANDAX-III project which plans to install a 200 kg gas XE TPC in the China Jinping Underground lab by 2017 as, if successful, a first step towards the tonne-scale experiment.

The T-REX group has designed, built and run two TREX-$\beta\beta$ prototypes: TREX-$\beta\beta$-0 is a small 2.2 l setup equipped with a 35 mm-diameter microbulk micromegas for first test and characterization of readouts at high pressure [8]; TREX-$\beta\beta$-1 is a prototype, originally developed as a demonstrator for NEXT able to contain 1 kg Xe fiducial at 10 bars, fully equipped pixelized readout and where Xe-TMA tests have been performed and first long e-tracks imaged [9] (figure 3). Software development

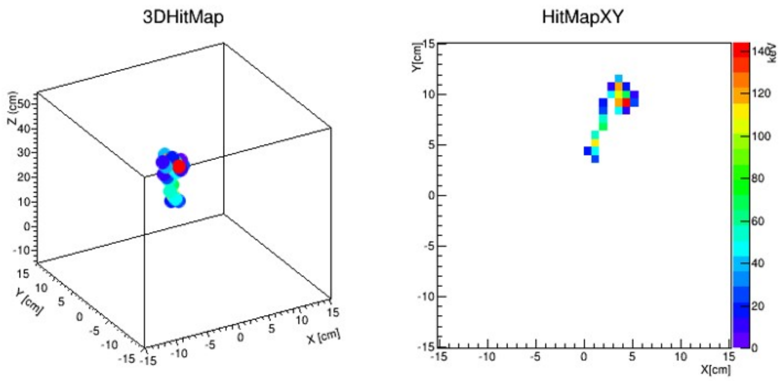

Figure 3. Reconstructed 3D tracks from ^{22}Na 1275 keV events, near the mean energy of one of the ^{136}Xe DBD electrons, in TREX-$\beta\beta$-1 Micromegas detector. The Bragg peak is well identified at the end of the track.

and prototype running are the basis for the work on four axes to probe that Micromegas-based HPXe TPC is a high competitive option for the next generation of DBD experiments (see [1] for more details):

1. Radiopurity. The radioactivity levels of microbulk Micromegas, as well as of other components of TPC setups (gas vessel, field cage, radiation shielding or electronic acquisition system), have been quantify or bound [10]. Values of Table 1 of [1] for Microbulk Micromegas readout planes point to levels of, or below, ~0.1 μBq/cm^2 for both ^{208}Tl and ^{214}Bi.

2. Work with xenon at high pressure. Microbulk Micromegas have been extensively studied in high pressure Xe and Xe mixtures. The addition of TMA at levels of ~ 1% reduces electron diffusion by up to a factor of 10–3 (transverse–longitudinal diffusion) with respect to pure Xe, improving the quality of the topological pattern, with sufficient gain, stability, homogeneity and good energy resolution (at least a ~ 3% FWHM @ $Q_{\beta\beta}$ - demonstrated experimentally for high-energy extended tracks at 10 bar-, and even down to a ~ 1%FWHM -extrapolated from low energy events-)

3. Imaging.

   (a) Pattern recognition. Firstly used to analyse and deeply understand backgrounds and signal signatures in simulations, first automated discrimination algorithms showed a reduction of the background level in around three orders of magnitude while keeping signal efficiency of 40% [11]. A lower diffusion in gas and a higher readout granularity will allow to consider additional subtler topological features improving pattern recognition.

   (b) Imaging of long electron tracks. Experimentally we have proven that the DBD ionization signature can be imaged with high quality [9] (figure 3).

4. Scalability. Work on Scalable Radiopure Readout Module (SR2M) concept for larger detectors as those foreseen in PANDAX.

TREX prospects in this line are continuing our collaboration with the PANDAX-III experiment and improving TREX-$\beta\beta$ results on the four axes afore mentioned [12].

4 Micromegas for low energy WIMP searches

Main stream Dark Matter experiments are focused on ~ 50–200 GeV WIMPs and require large masses of heavy target nuclei. The low mass range (< 10–20 GeV) is not reachable for such experiments due to the small recoil energy produced by the interaction of low mass WIMP in heavy nuclei which makes impossible the electron-nuclear recoil discrimination mechanism. To study masses below 20 GeV, new specific WIMP experiments are needed with lighter target materials and a low intrinsic energy threshold. Within the T-REX project a new approach for low mass WIMP

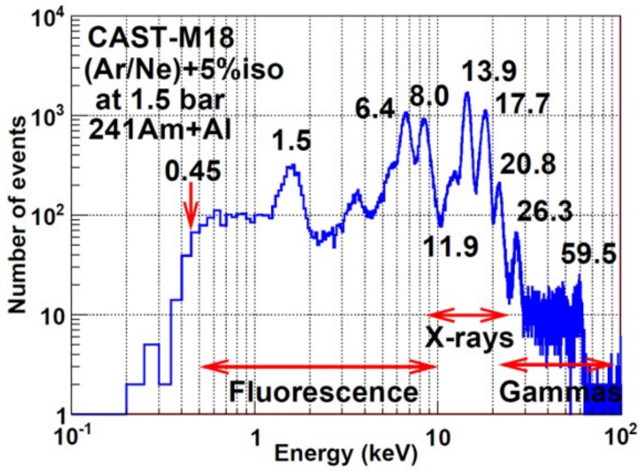

Figure 4. Energy spectrum of an ^{241}Am source+ Al foil calibration showing an energy threshold below 450 eV.

searches has been proposed based on gas TPCs with Micromegas readouts. As a large version of CAST/IAXO prototypes, the TREX-DM prototype will explore this concept [13]. Conceived to be operated underground and adequately shielded, it is not focused on directionality since it will operate at high pressure.

The detector setup is composed of a cylindrical vessel made of radiopure copper (0.5 m inner diameter, 0.5 m length and 6 cm of thickness) which can hold up to 10 bar of pressure, while constituting the innermost part of the shielding. A central mylar cathode separates the two active volumes, both of them equipped with a field cage (copper strips imprinted on a kapton substrate) and stripped bulk Micromegas as readout planes.

The R&D work for TREX-DM follows four lines:

1. Light target species as argon and neon. Gas mixtures as Ar+2%iC4H10 (^{39}Ar-depleted) and Ne+2%iC4H10 have been studied at 10 bars with an active mass of 0.300 kg and 0.160 kg respectively.

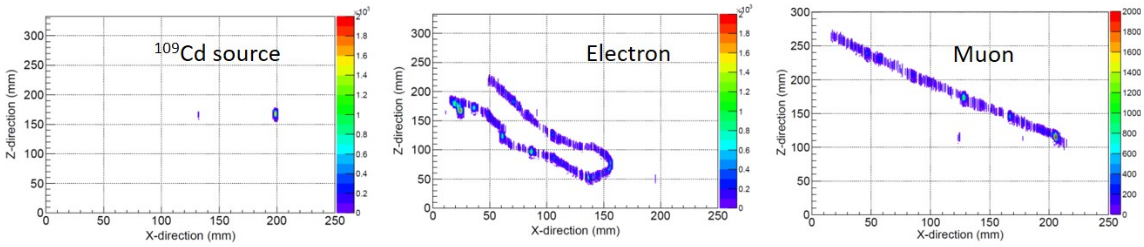

Figure 5. ^{109}Cd calibration, electron and muon tracks in TREX-DM.

2. Low energy threshold. A low energy threshold (< 450 eV) is feasible with the current AFTER-based data acquisition. A new autotrigger electronics, based on the AGET chip, to be implemented for the final setup, promises a reduction down to 0.1 keV.

3. Imaging. The expected signals in TREX-DM are nuclear recoils with energies below 20 keV which will create short tracks of a few microns length. To validate the full simulation chain, real and simulated data analysis were compared showing a reasonable level of agreement.

4. Low background. Fully built with radiopure materials, a first background model estimates around 4 counts keV^{-1} kg^{-1} day^{-1} in the (2–7) keV range. Values even lower than 0.1 counts keV^{-1} kg^{-1} day^{-1} in the 1–10 keV energy range are achievable both for argon and neon-based mixtures, with an 80% of signal efficiency.

The *Letter of Intent* of the TREX-DM experiment has been presented to the LSC (Laboratorio Subterráneo de Canfranc) scientific committee in May 2016 and we work at the moment in an experiment proposal to be presented in the next months for underground installation and operation.

5 A dedicated software: the REST framework

A dedicated Root and C++ based[1] software, REST code, has been developed to simulate physics interactions of particles, detector physics (diffusion, drift of ionization charges, amplification in Micromegas structure), readout and electronic response. Furthermore data can be also acquired and processed inside the REST framework. Viewers and analysis tools are common for simulated and real data.

This is a fast evolving code, which can be shared through Gitlab repository and will be ready for a stable version in Fall 2016. It could be adapted to other micro-pattern detectors.

6 Conclusions

The TREX project combines novel Micropattern developments and low background techniques to study the application of MicroMegas-read High Pressure TPCs to Rare Event Searches. These detectors show not only an excellent spatial resolution, but also a good energy resolution, are simple,

[1]It relies additionally on external codes as Geant4 for particle interaction simulation, and Garfield or Magboltz for detector physics and gas data.

robust, scalable and can be built with radiopure materials. Therefore, it is a really competitive technique for the new generation of experiments where the access to high topological information is essential and applications to other lines as medical imaging or neutron detection are open.

Prospects for the near future are encouraging: Axion searches in IAXO, double beta in PANDAX-III and the TREX-DM detector ready to be deployed in the LSC as a new technique for low energy WIMP searches, while we explore also other imaging industrial applications.

Acknowledgments

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