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RESEARCH ARTICLE

REVISED Micromegas with GEM preamplification for enhanced energy threshold in low-background gaseous time projection chambers

[version 2; peer review: 3 approved]

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Abstract

Background

We develop the concept of a Micromegas readout plane with an additional GEM preamplification stage placed a few millimetres above it to increase the maximum effective gain of the combined readout.

Methods

We implement it and test it in realistic conditions for its application to low-background dark matter searches like the TREX-DM experiment. For this, we use a Micromegas of Microbulk type, built with radiopure materials.

Results

We report on GEM effective extra gain factors of about 90, 50 and 20 in 1, 4 and 10 bar of Ar-1%iC_4H_{10}. These results are obtained in a small test chamber allowing for systematic scanning of voltages and pressures. In addition, a TREX-DM full-scale set-up has also been built and tested, featuring a replica of the fully-patterned TREX-DM

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Microbulk readout.

Conclusions

The results here obtained show promise to lower the threshold of the experiment down to 50 eV $_{ee}$, corresponding to substantially enhanced sensitivity to low-mass WIMPs.

Keywords
Dark Matter, WIMPs, Time Projection Chamber, Micromegas, Underground Science, Low Background Techniques, Radiopurity

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REVISED **Amendments from Version 1**

We have revised the paper in accordance with the comments from the reviewers:

- Throughout the manuscript, we have improved terminology consistency and addressed stylistic corrections as suggested by the reviewers.

- We have expanded the Introduction to highlight broader applications of Micromegas+TPC technology beyond astrophysics. We clarified the novelty of our work using Microbulk Micromegas while acknowledging previous implementations with bulk technology in the COMPASS experiment.

- The Methods section now includes more detailed discussions of systematic uncertainties and their sources, along with explanations of technical challenges encountered during measurements. We have enhanced transparency by providing additional information about our experimental setup, data acquisition processes, and analysis methods.

- We have added context in the Results section regarding observed phenomena in our gain curves and outlined our plans for future systematic studies to investigate these effects. The discussion of scalability concerns has been expanded to include potential solutions being explored for the full-scale implementation.

These revisions provide greater context for our experimental findings, acknowledge existing work in the field, address methodological concerns, and outline future research directions while maintaining the significance of our results.

Any further responses from the reviewers can be found at the end of the article

1 Introduction

Gaseous time projection chambers (TPCs) are versatile detectors that can measure the energy and track of ionizing particles in three dimensions. They have been widely used in various fields of physics, such as high-energy physics, nuclear physics, astroparticle physics and medical imaging[1]. One of the main advantages of TPCs is their ability to discriminate different types of particles based on their energy loss and track shape, which is crucial for reducing backgrounds in rare event searches. Modern incarnations of TPCs include micro-pattern gaseous detectors (MPGDs) as sensing planes. Example of these are the MICRO-MEsh GAseous Structure (Micromegas)[2] and Gas Electron Amplifiers (GEM)[3,4]. In recent years, TPCs with Micromegas readouts have also found significant applications beyond traditional physics research, including muography for geophysics, civil engineering, and archaeological studies[5,6], demonstrating their utility across diverse scientific disciplines.

Micromegas is a type of MPGD that consists of a thin metallic mesh placed O(50) μm above a segmented anode. The gas volume between the cathode and the mesh acts as a drift region, while the gas volume between the mesh and the anode acts as an amplification region. The electric field in the amplification region is much higher than in the drift region, creating an avalanche of electrons that induces a signal on the anode[2].

In Micromegas of the "Microbulk" type, the whole amplification structure is produced by chemical processing of a double-sided copper-clad polyamide laminate, onto which the mesh and the anode pattern are etched[7]. This type of detector is particularly well suited for low-background experiments thanks to its low intrinsic radioactivity[8]. Indeed, it has been intensely developed in dedicated R&D projects[9,10] and is now being used in solar axions[11,12], neutrinoless double beta decay[13] and direct dark matter searches[14–16].

Although achieving higher signal-to-noise ratio is always a desirable property for every application, low detection threshold is especially relevant in dark matter experiments aiming at the detection of the low-energy nuclear recoils produced by the collisions of galactic WIMPs with target nuclei. In these experiments, the spectral distribution of the signal concentrates at low recoil energy, exponentially decaying for higher values[17]. For experiments specifically targeting low-mass WIMPs, lowering the detector threshold is an important line of detector development, that automatically translates to better sensitivity, while allowing access to lower WIMP masses.

The intrinsic signal amplification happening in the Micromegas gap of the TPC, effectively decoupling the detector threshold from the total size of the TPC, is one of the appealing features that motivates the application of this technology in the TREX-DM experiment. TREX-DM[14] is a high-pressure, low-background, Micromegas-based TPC looking for low-mass WIMPs in the Canfranc Underground Laboratory under the Spanish Pyrenees. The TREX-DM TPC has been designed to have an active volume of 20 L, which translates into 0.32 kg of Argon mass at 10 bar (or, alternatively, 0.16 kg of Neon). It is composed of a cylindrical vessel made of radiopure copper, with a diameter of 0.5 m, a length of 0.5 m and a wall thickness of 6 cm. These dimensions are set by the requirements that the vessel holds up to 10 bar(a) of pressure, while at the same time constitutes the innermost part of the shielding. The vessel is divided into two active volumes by a central Mylar cathode, which is connected to high voltage by a tailor-made feedthrough. At each side, there is a 16-cm-long field cage defined by a series of copper strips imprinted on a Kapton substrate supported by four PTFE walls. At the two ends of the active volumes, two 25×25 cm^2 squared Microbulk Micromegas readouts are placed as sensing anodes, each of them patterned with ~ 1 mm pixels, interlinked with 512 strips in an $x - y$ layout.

Especially optimized Micromegas test set-ups have shown that very high gains, of even $>10^6$, are achievable[18]. However, the constraints imposed by the environment of a real experiment (the need for stable operation over long periods, robustness of operation, total absence of destructive discharges, large area, large readout segmentation, a controlled level of electronic noise, a given gas composition and pressure determined by physics, etc.) means that an energy threshold only somewhat lower than 1 keV is realistic for a Microbulk readout in an experiment like TREX-DM. Indeed, the target threshold of the experiment in its baseline configuration is 0.4 keV. The huge physics potential of lowering this parameter (potentially down to the single-electron level, ~ 20 eV) in terms of improved sensitivity (see Section 4) has prompted the investigation to increase the operational gain of the readout, by a preamplification stage that multiplies the primary electron cloud before entering the Microbulk gap, effectively contributing with an additional multiplication factor to the final readout gain. This preamplification stage consists of a Gas Electron Multiplication (GEM) foil, which is made of a copper-clad (on both sides), 50-μm-thick Kapton foil, perforated by a high density, regular matrix of holes. The primary electrons go through the holes and get multiplied by a factor depending on the voltage applied between the electrodes. The raw materials of GEM foils are identical to the ones of Microbulk planes, which makes this option promising for low-background searches.

In this article, we report on a study of a hybrid GEM plus Microbulk readout. The combination of a GEM and a Micromegas (GEM + MM henceforth) has been tested in the past[19] and successfully implemented in real experiments such as COMPASS[20,21] using bulk technology, but this is the first time this is done with a Microbulk Micromegas, at high pressures, and in the context of low-background constraints.

In order to perform the study, a test set-up has been built and operated, as described in Subsection 2.1. The results of the characterization of the combined readout are presented in Subsection 3.1. Later on, another set-up with a full-scale GEM foil installed on top of an exact replica of the TREX-DM Microbulks, simulating the real installation to be done in the TREX-DM experiment, is prepared to demonstrate the feasibility of this solution to enhance the threshold of the experiment. The description and results with this larger-scale set-up are presented in Subsection 2.2 and Subsection 3.2. We briefly discuss in Section 4 the sensitivity projections that the improvement in threshold of this work could potentially bring to an enhanced TREX-DM experiment. We finish with our conclusions in Section 5.

2 Methods

This section is devoted to the description of the experimental set-ups used to obtain the results presented in this article.

2.1 Description of the test set-up

The Microbulk Micromegas detector with the GEM preamplification stage is placed inside a small (2.4 L) stainless-steel chamber certified to withstand 12 bar. The vacuum level achieved in this chamber after ~ 1 h with a Pfeiffer Vacuum HiCube 80 Classic Turbo Pump is ~ 10^{-5} mbar. The gas used in these studies is Ar-1%iC_4H_{10}, though it is intended to extend them to other Ar- and Ne-based mixtures of interest to TREX-DM (such as Ar-10%iC_4H_{10}).

The Microbulk Micromegas detector lies on top of a metallic support plate, separated from it by a PTFE piece. The Micromegas used has a non-segmented and disc-shaped anode with a small 2-cm-diameter circular active area (cathode). The gap between mesh and anode is 50 μm. Several Micromegas with varying hole diameters (50–60 μm) and hole pitch (100–110 μm) are used in these tests. A GEM stage of roughly the same active area is mounted on top of the mesh, at a distance L_{transfer} = 10 mm. The GEM has a thickness of 60 μm (50 μm the Kapton, 5 μm each copper layer), hole pitch of 140 μm, diameter of holes in copper of 70 μm and diameter of holes in Kapton of 60 μm. Finally, a cathode (a stainless-steel grid) is placed above the GEM, at a distance L_{drift} = 13 mm. The cathode has a ^{55}Fe source attached (K-alpha X-ray at 5.9 keV) facing the ionization volume.

As for the voltages, the anode is kept grounded, the mesh at V_{mesh}, the bottom and top layers of the GEM at V_{bottom} and V_{top}, respectively (we define the GEM preamplification voltage as $V_{\text{GEM}} = V_{\text{top}} - V_{\text{bottom}}$), and the cathode at V_{cath}. The metallic support plate is kept at $V_{\text{plate}} = V_{\text{mesh}}$ to avoid potential distortions in the transfer field E_{transfer}. Two CAEN HV power supply modules (a 4-channel N1471H and a 2-channel N471A) are used to provide these voltages.

A schematic view of the set-up can be seen in Figure 1, and images of the different elements are shown in Figure 2.

Regarding the DAQ, the signal from the anode is first sent to a preamplifier (Canberra Model 2005), and then it goes through an amplifier module (Canberra Model 2022 NIM module). Both the preamplified and the amplified signals are read with an oscilloscope (a Tektronix TDS5054). A custom-made data-taking and analysis software is used to control the oscilloscope and process the data. This software enables remote operation via Ethernet connection to the local network, automating the data acquisition process from a PC. It records the individual pulses that compose each event, which are then analyzed to extract key signal parameters such as maximum amplitude, rise time or pulse area. While this set-up has been optimized for our specific experimental configuration, we are open to providing additional technical details to researchers interested in reproducing these results.

2.2 Description of the full-scale TREX-DM set-up

As already explained in Section 1, the motivation to explore the combination GEM + MM detector is to reduce the energy threshold in the low-mass WIMPs search carried out by TREX-DM. Therefore, although the results for a small set-up that will be described in Subsection 3.1 look promising, a deeper investigation is required to determine if they are also achievable in real experimental conditions (essentially, a much larger readout area and drift distance). To this end, a test bench is prepared with a stainless-steel 50 L chamber containing a spare detector identical to the ones installed in TREX-DM and a GEM foil on top. This chamber achieves a vacuum level of ~ 10 mbar using a Pfeiffer Vacuum HiCube 80 Classic Turbo Pump during ~ 1 h, then it is filled with Ar-1%iC_4H_{10}, and a flow of 8 L h^{-1} is set during 72 h to ensure good quality of the gas. During these tests, the pressure has been set to 1 bar due to design specifications of the chamber. The Microbulk Micromegas detector lies on top of the endcap of the chamber. As already mentioned, the readout plane has a 25×25 cm^2 square active area, patterned with 512 strips (256 in each direction) with the mesh gap being 50 μm. A GEM foil of the same dimensions and gap is placed above the mesh, at a distance L_{transfer} = 10 mm. Finally, the cathode (a stainless-steel grid) is placed above the GEM, at a distance L_{drift} = 100 mm. The cathode has two ^{109}Cd radioactive sources attached (K-alpha X-ray at 22.1 keV).

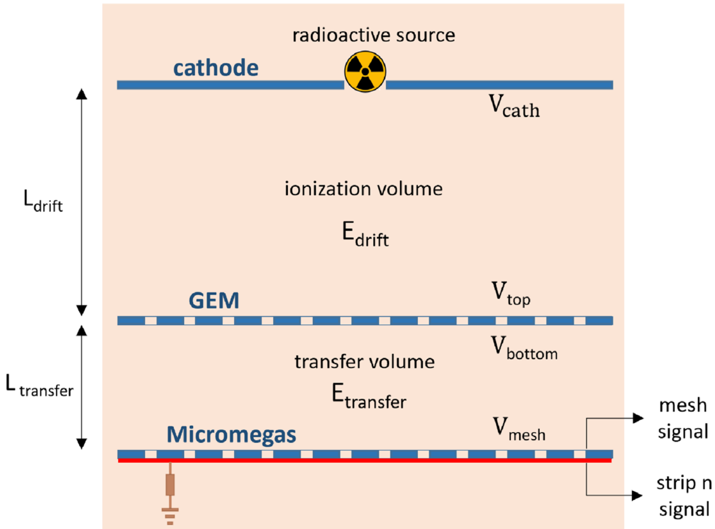


Figure 1. Schematic view of the different elements of the set-up (Micromegas, GEM, cathode, calibration source) along with the relevant parameters ($L_{transfer}$, L_{drift}, $E_{transfer}$, E_{drift}, V_{mesh}, V_{bottom}, V_{top}, V_{cath}).

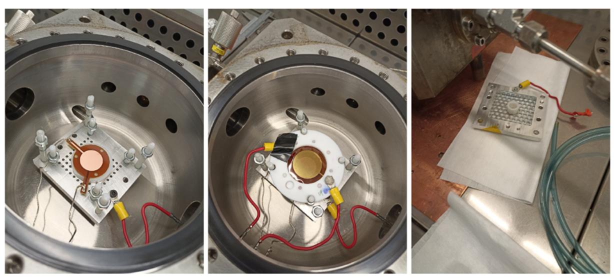


Figure 2. Left: metallic support plate inside the vessel with the 2-cm-diameter Microbulk Micromegas on top. The inner PTFE pillars support the GEM at the appropriate distance, while the outer PTFE pillars are used to hold the cathode. The anode, mesh and plate connections to the feedthroughs are shown. Center: GEM foil mounted on top of the Micromegas, along with the HV connections. Right: Cathode with ^{55}Fe source attached facing down.

Again, as described in Subsection 2.1, the mesh is kept at V_{mesh}, the bottom and top layers of the GEM at V_{bottom} and V_{top}, with $V_{GEM} = V_{top} - V_{bottom}$, and the cathode at V_{cath}. The same CAEN HV power supply N1471H is used in this test. To read out the signals from the TPC, a combination composed of a Front-End Card (FEC) with AGET (ASIC for General Electronic readout of TPCs) chips[22] and a Feminos card[23] is used. Both the FEC and the Feminos are custom-made electronics cards developed by CEA Saclay as a solution for data acquisition in nuclear and high-energy physics experiments. Each FEC has 4 AGETs, each of them with 64 channels, which makes them ideal for high-granularity readouts such as the ones used in TREX-DM. The AGETs generate the trigger based on the signal (it can be fine-tuned to trigger on single-channel pulses), and they provide the amplification, shaping and storage of the analog signals. On the other hand, the Feminos interfaces with the AGETs to digitize the analog signals (with 12-bit precision) and aggregate them into coherent events. This allows for high-speed data transfer from the Feminos towards the back-end DAQ, namely a computer using a custom-made software to interface with the Feminos card and handle the data acquisition and storage into .aqs files (raw data files). To process and analyze the data, an analysis routine based on REST-for-Physics[24], a custom-made software framework developed for the analysis of data from rare event search experiments, is implemented.

The schematic view of the set-up is shown in Figure 1, and images of the assembly of all the parts of the set-up can be seen in Figure 3.

3 Results

This section contains the main results derived from the operation of the test set-up and the full-scale setup described in Section 2.

3.1 Results from the test set-up

The goal is to obtain the relative amplification factor provided by the extra GEM stage with respect to only-Micromegas runs. To this end, both only-Micromegas (V_{mesh} ON, $V_{GEM} = 0$) and Micromegas+GEM (V_{mesh} and V_{GEM} ON) calibration runs are

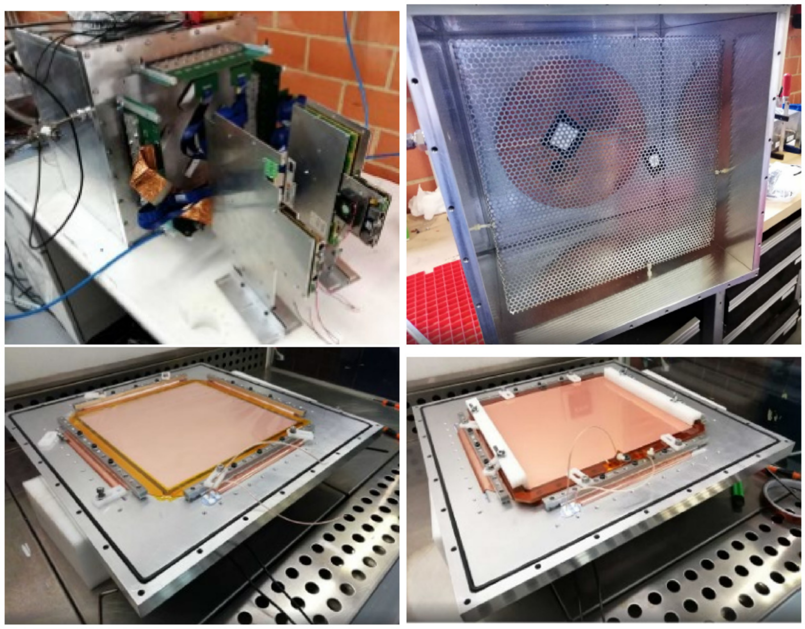


Figure 3. Top left: closed vessel with DAQ. Top right: cathode with two ^{109}Cd radioactive sources (attached with black tape). Bottom left: Micromegas detector secured on the endcap of the chamber. Bottom right: GEM foil placed on top of the mesh.

taken. We define the preamplification factor as the extra gain added by the GEM relative to a fixed Micromegas-induced gain. This is the natural extra gain parameter that arises when adding a second amplifying stage. However, in real experimental conditions, the maximum voltage that can be reached with the Micromegas alone is higher than the one that can be achieved with the GEM stage. Therefore, we define the GEM effective extra gain factor, GEM extra factor for short, as the amplification provided by the GEM in the optimized GEM + MM set-up with respect to the optimized only-Micromegas set-up. The chosen gas mixture for this study is Ar-1%iC_4H_{10}, due to its importance both for IAXO[25] and TREX-DM, the main experimental pursuits of the authors, and its immediate availability. Both the preamplification factor and the GEM extra factor are obtained at 1, 4 and 10 bar (target pressure in TREX-DM). The only missing value is the preamplification factor at 1 bar, due to noise problems in the set-up at that pressure the day when those data were taken. These noise issues were traced back to fluctuations in the preamplifier and amplifier modules. Despite attempts at mitigation, including substituting alternative preamplifier and amplifier modules, we were unable to sufficiently reduce the noise. However, since the relevant parameter and focus of our efforts, the GEM extra factor, had already been measured, we proceeded with the rest of the measurements. We note that further work on noise reduction for this set-up is ongoing.

The comparison of both GEM + MM and only-Micromegas spectra is done within the same dynamical range of a given electronics setup, to avoid systematics derived from different electronic gains. Thus, one must be careful selecting the parameters of the DAQ electronics, as it is easy to saturate the amplifier module with the GEM-preamplified signals. In this way, direct comparison of energy spectra like the ones shown in Figure 4 can be made.

The operation points with highest stable voltages achieved for the set-up described in Subsection 2.1 are summarised in Table 1. A reference value for the maximum voltage for only V_{mesh} runs was obtained from 26. For combined runs, the starting point for both V_{mesh} and V_{GEM} was a safe value, around 30–40 V below the reference voltage. From that value, the voltage was raised little by little, in 5 V increments, first in V_{mesh} and then in V_{GEM}, until reaching unstable behaviour (generally sparks). It was observed, however, that for the last stable voltage in V_{mesh}, V_{GEM} could still be pushed a bit further up.

Here, in all cases, E_{drift} = 100 V cm^{-1} bar^{-1} and $E_{transfer}$ = 100 V cm^{-1} bar^{-1}, values which usually lie within the electron transmission plateau of the Micromegas. However, border effects cannot be excluded given the size of the active areas and the absence of a field shaper, so these values might not represent the optimal operating conditions. Nevertheless, given that the purpose of this set-up was just to prove the feasibility and potential of the combined GEM + MM system when installed in real experimental conditions in TREX-DM, detailed field optimizations were not the focus at this stage, and therefore, the in-depth study about the electron transmission (and gain curves) of the GEM + MM was left for the full-scale set-up in Subsection 3.2.

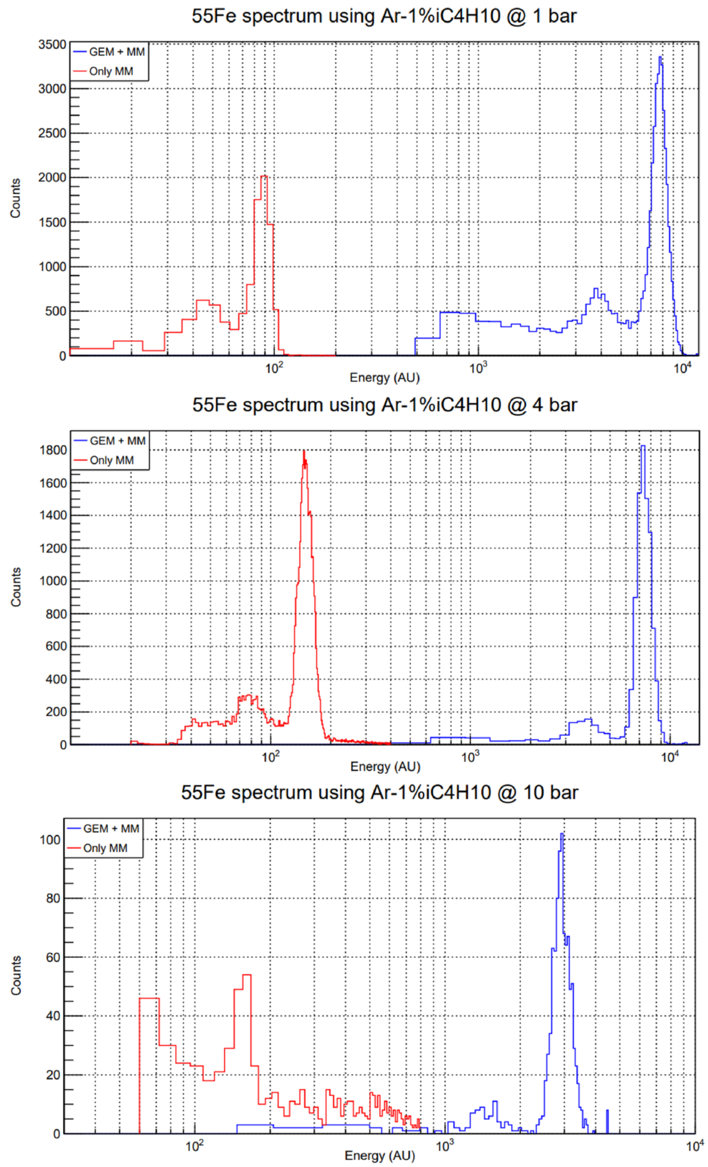


Figure 4. Energy spectra comparison between only MM (red) and GEM + MM (blue) calibrations using a ^{55}Fe source in the test set-up. The gas mixture is Ar-1%iC_4H_{10}. Note that the horizontal axis is presented in logarithmic scale. Top: 1 bar, GEM extra factor ≈ 90; middle: 4 bar, GEM extra factor ≈ 50; bottom: 10 bar, GEM extra factor ≈ 20. The voltages of these runs are the ones recorded in the fifth column (red lines) and second and third columns (blue lines) of Table 1.

Table 1. GEM extra factors and preamplification factors achieved for the two set-ups at different pressures, defined as the gain ratio between GEM + MM runs ($V_{GEM} \neq 0$ V) and only Micromegas runs ($V_{GEM} = 0$ V). The first three entries correspond to the test set-up, while the fourth line belongs to the full-scale set-up.

Pressure (bar)	V_{mesh} (V) (GEM + MM system)	V_{GEM} (V) (GEM + MM system)	Preamp. factor	V_{mesh} (V) (only-MM system)	GEM effective extra gain factor
1	305	310	-	315	90
4	390	410	70	400	50
10	535	550	21	540	19
1	290	285	85	293	80

Comparison of the position of the 5.9 keV peak in ^{55}Fe calibration runs points to maximum GEM extra factors of 90 (1 bar), 50 (4 bar) and 20 (10 bar). These factors have been reproduced over several days and for different Micromegas detectors with the same micropattern, and all of them are contained within a range of ±20%. This variation inherently represents the systematic uncertainty in our measurements, mainly arising from slight differences in the highest stable voltages achieved (usually ± 5 V either in V_{mesh}, V_{GEM} or both), as well as environmental fluctuations in temperature and pressure during the measurement period. The decrease in gain with pressure is expected in MPGDs in general (even though Microbulk Micromegas do not display such a pronounced performance degradation at high pressures)[27]. However, a more comprehensive theoretical analysis comparing these observed gain trends with expectations from existing models and simulations is left for future work.

Several examples of this comparison are shown in Figure 4. In the case of 10 bar, the only-Micromegas runs are more difficult to take, because the mean free path of 5.9 keV photons in Ar-1%iC_4H_{10} at that pressure is 2.3 mm[28], and those that do not get absorbed in the drift volume have to go through the GEM foil. Therefore, the exponential background is already noticeable and the calibration peak is less intense, but still clearly visible. All the resolutions (in %FWHM), with and without preamplification, are around 20%, except for the only-Micromegas run at 10 bar, which is around 30%, mainly due to the problem with the small number of events mentioned above. However, this result points to no significant degradation in resolution when adding a preamplification stage.

3.2 Results from the full-scale TREX-DM set-up

Although the initial goal was to replicate the results from the small set-up at 1 bar discussed in Subsection 3.1, some more tests are performed in this full-scale set-up.

In particular, the electron transmission (transparency curves) of the GEM foil and the mesh is studied. The results are shown in Figure 5. As for the GEM transmission, it can be seen that a plateau is reached very quickly, even for very low drift field values. This is expected, because in previous studies of electron transmission in GEMs[29], it has been shown that collection efficiency increases with V_{GEM}, meaning that full transparency is achieved with lower E_{drift} as V_{GEM} goes up. Regarding the Micromegas curves, an interesting phenomenon occurs at $E_{transfer}$ = 0 V cm^{-1} bar^{-1}, because the relative gain has a non-zero value: the photons converted in the drift volume are amplified through the GEM, and thanks to the proximity to the mesh, diffusion is enough for some of the events to reach the Micromegas, where they are amplified again. This effect is possibly explained by the fact that $L_{transfer}$ is small, ~ 1 cm, but tests at different transfer distances would be necessary to shed light on this. On the other hand, the relative gain remains roughly constant from $E_{transfer}$ ≈ 150 V cm^{-1} bar^{-1}. This result is unanticipated, because the transparency curve is expected to depend on the extraction efficiency of the GEM bottom layer and the collection efficiency of the Micromegas. While this plateau is usual for the Micromegas collection efficiency, one would expect the extraction efficiency of the GEM to increase in this region, up to a few kV cm^{-1} bar^{-1}[30]. We do not have a conclusive explanation for this, but several hypotheses are being considered:

- What we think is a plateau is a slowly rising curve. Due to voltage limitations of the set-up, it is not possible to go further beyond ~ 1 kV cm^{-1} bar^{-1}, so perhaps there is a gain increase up to a few kV cm^{-1} bar^{-1}.

- The gas mixture is playing an important role in the shape of the curves. Normally, GEM detectors use noble gases in combination with gases such as CH_4 or CF_4 due to their high drift velocities and

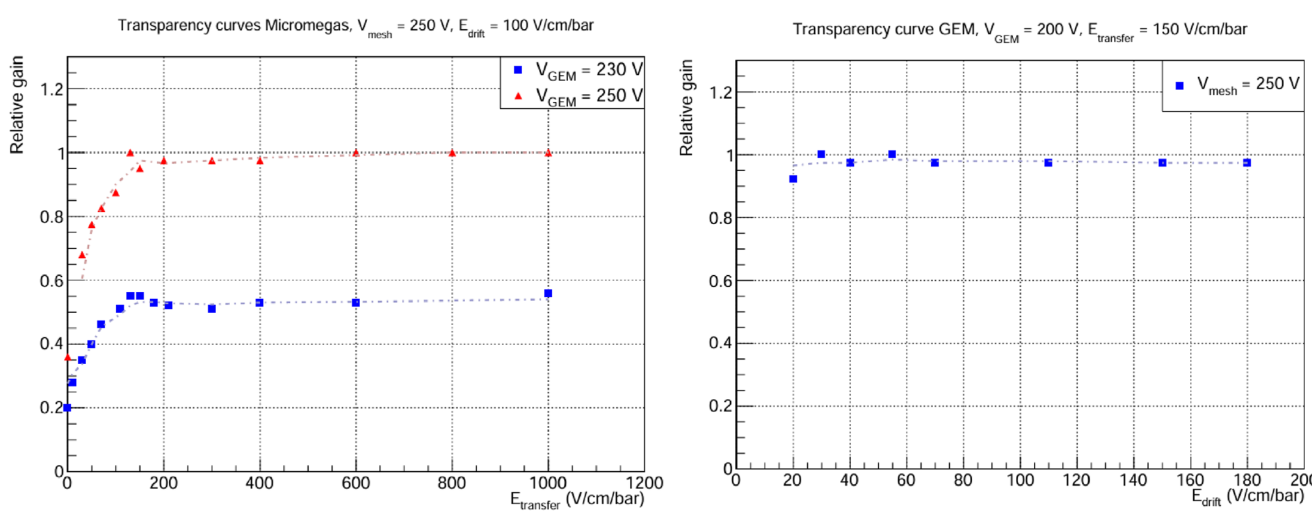


Figure 5. Electron transmission curves. The *y* axis corresponds to the mean peak position, normalized to the highest value. Statistical errors in both plots are < 1%. Left: Micromegas transmission for fixed mesh voltage and two different GEM voltages. E_{drift} = 100 V cm^{-1} bar^{-1} because there is total transparency in the GEM for that drift field. Right: GEM transmission for fixed mesh and GEM voltages. $E_{transfer}$ = 150 V cm^{-1} bar^{-1} in order to be at the plateau of the Micromegas transparency curve.

low diffusion coefficients with respect to other quenchers such as iC_4H_{10}[31]. To the best of our knowledge, the mixture Ar-1%iC_4H_{10} has not been characterised in the context of GEMs, and it could be the case that its higher diffusion coefficients imply a loss of extraction efficiency from the bottom layer of the GEM.

Irrespective of the reason, it should be noted that this unexplained behaviour does not invalidate the results: at most, an optimisation of the extraction efficiency would yield higher gains, and thus larger GEM extra factors.

Also, gain curves are studied before the determination of the maximum GEM extra factor. As it can be seen in Figure 6, two types of gain curves are examined: Micromegas gain curves (varying V_{mesh} for a fixed V_{GEM}) and GEM gain curves (varying V_{GEM} for a fixed V_{mesh}). In both cases, the expected exponential behaviour with amplification voltage is observed. In the Micromegas curves, the special case V_{GEM} = 0 V is also included, which corresponds to the baseline only-Micromegas detector. Comparison of this curve with the GEM + MM curves already hints at extra gain factors of O(10) thanks to the GEM addition. In all cases, it can be seen that the curves are not perfectly parallel (in log scale). This suggests both stages are not totally factorizable, possibly due to ion backflow or other complex interactions between the GEM and Micromegas stages. To investigate this effect further, a dedicated set-up based on a small chamber similar to the one presented in Subsection 2.1 is being prepared in Zaragoza. In this set-up, we will perform systematic studies using UV laser calibration techniques with a photocathode. Furthermore, measurements with the GEM positioned at different distances relative to the Micromegas are planned to better understand these interactions. While a more detailed analysis will be the subject of future work, it is not critical for the primary objectives of this paper.

Lastly, some more data are taken in order to explore the value for the maximum GEM extra factor and preamplification factor achievable. In the fourth row of Table 1, the achieved voltages are shown. Comparison of the position of the 8 keV copper fluorescence peak in ^{109}Cd calibration runs (see Figure 7) yields a GEM extra factor of 80, in line with the result obtained in Subsection 3.1. In these runs, E_{drift} = 100 V cm^{-1} bar^{-1}, $E_{transfer}$ = 150 V cm^{-1} bar^{-1} as suggested by the transparency curves.

Note that the voltages are lower than those presented in Subsection 3.1 because of the intrinsic difficulty associated to operating larger-area Micromegas (1 vs. 1024 channels means higher possibility of leakage currents between mesh and some channels). To address this challenge, we are investigating the implementation of resistive Micromegas technology[32], which has shown improved stability against spark formation in similar applications. This approach could potentially allow operation at higher voltages in the full-scale detector, bringing performance closer to that observed in the small-scale tests. Despite the current voltage limitations, the potential to lower the energy threshold is still present even in the full-scale set-up, mimicking the real experimental conditions of TREX-DM.

4 Discussion

This section discusses the impact the results presented in Section 3 have on the sensitivity of TREX-DM. As argued in the introduction, there is a strong motivation to extend the sensitivity of dark matter experiments to lower WIMP masses.

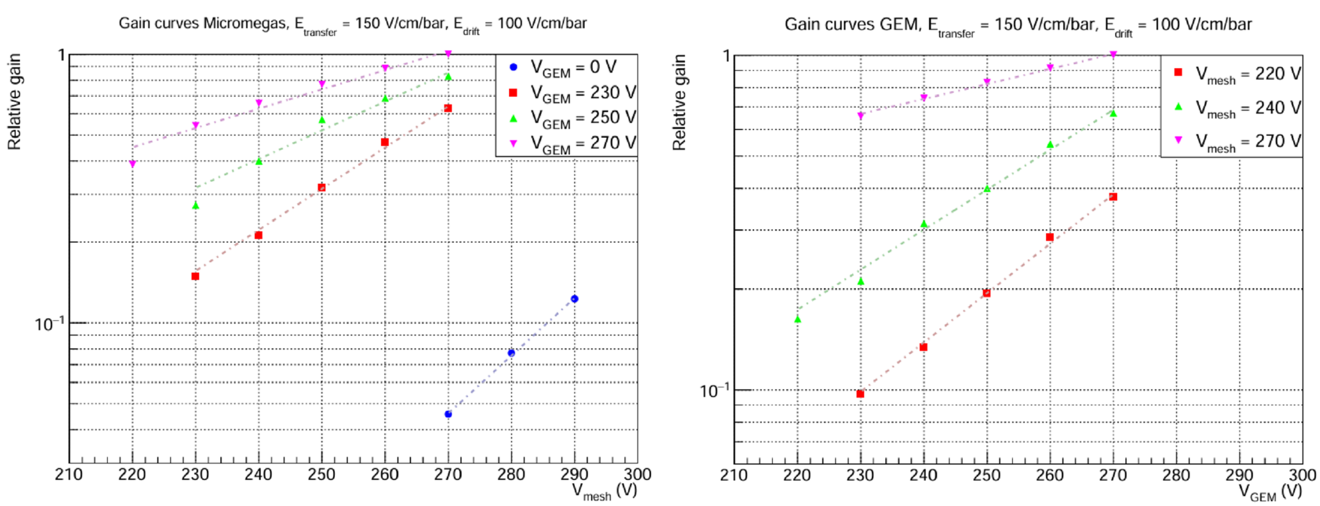


Figure 6. Gain curves. The *y* axis corresponds to the mean peak position, normalized to the highest value. Statistical errors in both plots are < 1%. Left: Micromegas curves for fixed V_{GEM} . Right: GEM curves for fixed V_{mesh}. In both cases, E_{drift} and $E_{transfer}$ are fixed. Note that the maximum gain corresponds to the same data point in both plots (V_{mesh} = 270 V, V_{GEM} = 270 V), so the relative gain is directly comparable between plots.

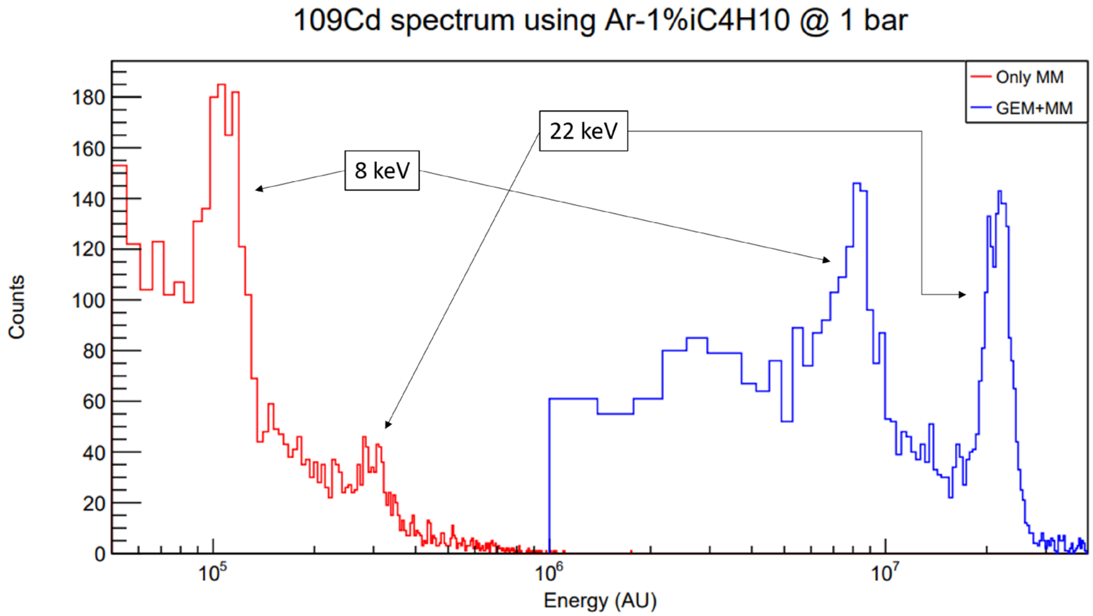


Figure 7. Energy spectrum comparison between only MM and GEM + MM calibrations using a ^{109}Cd source in the full-scale set-up. The 8 keV peak corresponds to the copper fluorescence at the Micromegas surface. The gas mixture is Ar-1%iC_4H_{10} at 1 bar. Note the horizontal axis is presented in logarithmic scale, and that an energy cut has been applied to the GEM + MM run in order to remove background and keep the left part of the canvas clean.

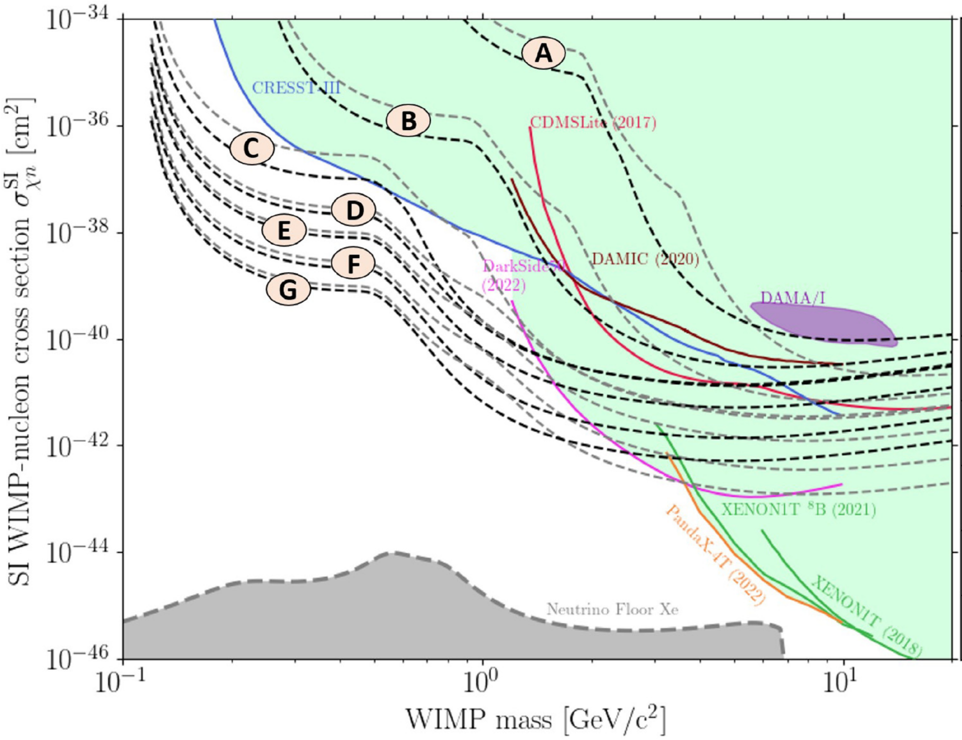
This requires lowering energy thresholds, as well as reducing the background at the lowest energies.

As of 2022, TREX-DM achieved a background level at low energies of around 80 dru (dru = c keV^{-1} day^{-1} kg^{-1}), and an energy threshold around 900 eV$_{ee}$. Reducing the threshold from 900 eV$_{ee}$ to 50 eV$_{ee}$ significantly enhances sensitivity in the < 1 GeV c^{-2} region. As already demonstrated in this paper, a great improvement in energy threshold can be achieved by introducing a new electron preamplification stage (the GEM) atop the Micromegas. Laboratory tests (Subsection 3.1 and Subsection 3.2) have proven GEM extra factors ranging from 20 to 90 are feasible, contingent on gas pressure.

In Figure 8, the sensitivity projections in TREX-DM for Spin Independent WIMP-nucleon interaction over a year are shown, considering several experimental parameters: energy threshold, background level and isobutane content of the gas mixture. The background level is expected to improve in the near term (there is a roadmap of upgrades underway, but the details are beyond the scope of this paper). On the other hand, optimizing the gas mixture plays a pivotal role. Sensitivity estimates indicate better performance with neon-based mixtures compared to argon. Also, argon mixtures with increased isobutane content are being considered: more isobutane enhances sensitivity to WIMPs below 1 GeV c^{-2} due to the lower mass of target nuclei. Even though these mixtures have not been studied in this paper, the preamplification results shown here are expected to hold because Ar-1%iC_4H_{10} is a conservative mixture choice: neon-based mixtures typically provide higher gains[26], and an increased isobutane content also goes in the direction of attaining greater amplifications.

5 Conclusions

Electron amplification in gas offers an attractive strategy to increase signal-to-noise ratio and therefore to reduce detector energy thresholds. This feature, coupled with the ability of building radiopure readout Micromegas planes with the Microbulk technology, is at the core of the TREX-DM proposal. In this paper, we have demonstrated the feasibility of an amplification scheme that should allow to approach the single-electron sensitivity in realistic TREX-DM implementations. The addition of a GEM preamplification stage on top of the Microbulk readout allows for this gain, without jeopardizing the radiopurity specifications of the readout. At the time of writing this article, a GEM + MM combined readout like the one tested in Subsection 2.2 is being installed and commissioned at the TREX-DM experiment. As discussed in Section 4, this improvement would open a new detection window at lower recoil energies that, depending on the background levels achieved at those energies, might lead to substantial improvement to low mass WIMPs, potentially down to an unexplored region of the parameter space.



scenario	base of mixture	energy thr (eV_{ee})	backgr level (dru)	Isobutane (%)	Exposed volume (L)
A	Ne	900	80	2	20
	Ar	900	80	1	20
B	Ne	200	30	2	20
	Ar	200	30	1	20
C	Ne	50	10	2	20
	Ar	50	10	1	20
D	Ne	50	10	10	20
	Ar	50	10	10	20
E	Ne	50	1	10	20
	Ar	50	1	10	20
F	Ne	50	1	10	200
	Ar	50	1	10	200
G	Ne	50	0.1	10	200
	Ar	50	0.1	10	200

Figure 8. WIMP-nucleon cross-section vs. WIMP mass exclusion plot, with current bounds from experiments[33–39], claimed discovery[40] and different scenarios for TREX-DM (all of them 1 year of exposure time). Each scenario is plotted with Ne-based (black) and Ar-based (grey) mixtures. Also, solar neutrino floor with a Xe target is shown[41].

Data availability

Underlying data

Zenodo: Data for manuscript submitted to Open Research Europe with title "Micromegas with GEM preamplification for enhanced energy threshold in low-background gaseous time projection chambers", https://doi.org/10.5281/zenodo.14525554

This project contains the following underlying data:

- Spectra for the test set-up:
  - spectrum_test_set-up_1_bar_only_MM.root (1 bar, only MM)
  - spectrum_test_set-up_1_bar_GEM_MM.root (1 bar, GEM+MM)
  - spectrum_test_set-up_4_bar_only_MM.root (4 bar, only MM)
  - spectrum_test_set-up_4_bar_GEM_MM.root (4 bar, GEM+MM)
  - spectrum_test_set-up_10_bar_only_MM.root (10 bar, only MM)
  - spectrum_test_set-up_10_bar_GEM_MM.root (10 bar, GEM+MM)
- Spectrum for the full-scale set-up:
  - spectrum_full-scale_set-up_1_bar_only_MM.root (1 bar, only MM)
  - spectrum_full-scale_set-up_1_bar_GEM_MM.root (1 bar, GEM+MM)
- Transparency curves for the full-scale set-up:
  - transparency_curve_micromegas_Edrift100_Vmesh250_Vgem230_full-scale_set-up.txt
  - transparency_curve_micromegas_Edrift100_Vmesh250_Vgem250_full-scale_set-up.txt
  - transparency_curve_gem_Etransfer150_Vmesh250_Vgem200_full-scale_set-up.txt
- GEM gain curves for the full-scale set-up:
  - gain_curve_gem_Etransfer150_Edrift100_Vmesh220_full-scale_set-up.txt

  - gain_curve_gem_Etransfer150_Edrift100_Vmesh240_full-scale_set-up.txt
  - gain_curve_gem_Etransfer150_Edrift100_Vmesh270_full-scale_set-up.txt

- Micromegas gain curves for the full-scale set-up:
  - gain_curve_micromegas_Etransfer150_Edrift100_Vgem0_full-scale_set-up.txt
  - gain_curve_micromegas_Etransfer150_Edrift100_Vgem230_full-scale_set-up.txt
  - gain_curve_micromegas_Etransfer150_Edrift100_Vgem250_full-scale_set-up.txt
  - gain_curve_micromegas_Etransfer150_Edrift100_Vgem270_full-scale_set-up.txt

Note: the .root format is associated to ROOT, the CERN open-source data analysis framework (https://root.cern/).

Acknowledgments

We would like to thank the Servicio General de Apoyo a la Investigación-SAI, Universidad de Zaragoza, for their technical support, and the Micro-Pattern Technologies (MPT) workshop at CERN, where both the Micromegas and the GEMs used in this article were manufactured.

This article has also been published on arXiv. It is available at https://doi.org/10.48550/arXiv.2412.19864.

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Open Peer Review

Current Peer Review Status: ✔ ✔ ✔

Version 2

Reviewer Report 02 April 2025

https://doi.org/10.21956/openreseurope.21540.r52294

✔ **Ludovic Mathieu**
Laboratoire de Physique des 2 infinis, Orsay, France

This paper presents an innovative approach to boost the gain of gaseous detector by combining GEM and Micromegas technology: primary electrons are multiplied by the GEM planed before being multiplied again in the Micromegas stage. This structure has several additional parameters (GEM spacing, GEM voltage, drift field) compared to Micromegas-only detectors, the influence of which are studied in this paper.

The aim of the gain improvement is to lower the energy threshold of such detector. This will be of primary importance for dark matter detection. This paper presents experiments carried out on a test setup-up, as well as its transposition to the full-scale TREX-DM setup.

Several comments have already been done by the two previous reviewers, and they have been addressed by the authors.

I don't have major corrections to request, just minor remarks:

- section 3.1, concerning the variation between different Micromegas detectors: the mesh is placed above the detection plane on pillars ; even if checked the fabrication process can induce small variations of the pillars height, inducing non-negligible differences on the Micromegas gain
- gain: the authors explain the gain increase they measure, but never mention the absolute value of this gain ; although not mandatory for their results, this information could be an interesting addition
- maximum voltage: the authors announce that the maximum voltage is lower for GEM+MM than it is for MM-only ; an explanation (or hypothesis) could be valuable

Best regards

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?

Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Nuclear instrumentation

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 20 March 2025

https://doi.org/10.21956/openreseurope.21540.r52247

Ignacio Lázaro Roche
[1] CNRS Delegation Provence et Corse, CNRS Delegation Provence et Corse, Rustrel, Provence-Alpes-Côte d'Azur, France
[2] Avignon University, Rustrel, France

The version 2 of the article takes into account all the remarks made by the 2 reviewers and is suitable for acceptation.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: -MPGD detectors, micromegas, time projection chambers, underground science, low background, dark matter

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 19 March 2025

https://doi.org/10.21956/openreseurope.21540.r52248

David Attié
Université Paris-Saclay, Gif-Sur-Yvette, France

Dear Authors

Most of the corrections and comments have been considered.

Only one minor correction is missing:
- §3.1
  > In 5th paragraph, change "microbulk" to "Microbulk".

After this very minor correction, the article can be indexed.

Best regards,

The reviewer.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?

Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Micromegas detector, TPC, MPGD

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Author Response 20 Mar 2025
Óscar Pérez Lázaro

Dear reviewer, The minor typo we missed has been corrected. Thank you again for your comments and the thorough review of the paper. Best regards, The authors

Competing Interests: No competing interests were disclosed.

Version 1

Reviewer Report 05 March 2025

https://doi.org/10.21956/openreseurope.20846.r51384

?

Ignacio Lázaro Roche
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[4] Avignon University, Rustrel, France

This article presents a study on the implementation of a preamplification stage using Gas Electron Multipliers (GEM) combined with microbulk Micromegas in gaseous time projection chambers (TPCs), aiming to lower the detection threshold. Two experimental setups are described: a small-scale test system and a larger-scale version with characteristics representative of TREX-DM.

Section 2 provides a thorough technical description of the detectors and their operation, detailing key parameters such as system geometry, gas conditions, and electronic characteristics. The motivation behind this approach is well-justified, as reducing the detection threshold is critical for improving sensitivity to low-energy nuclear recoils. The authors highlight the potential of the GEM + Micromegas combination, particularly in terms of achieving higher effective gains and maintaining stable operation under experimental constraints.

Section 3 provides a well-structured and data-rich presentation of GEM + MM performance. The results are encouraging for TREX-DM, particularly in achieving a lower energy threshold. However, the section would benefit from a more rigorous discussion of systematic uncertainties, theoretical interpretations, and potential improvements to the experimental design. Addressing these points would enhance confidence in the broader applicability of these findings to future large-scale detectors.

While the manuscript is technically sound and the experimental methodology is well outlined, there are areas where further clarification would strengthen the study. Firstly, although previous works on GEM + Micromegas setups are mentioned, a more detailed discussion of how this implementation differs from or improves upon prior efforts would provide better context. Secondly, while the feasibility of the approach is demonstrated, the long-term stability of the combined readout under real experimental conditions (e.g., extended operation in TREX-DM) is not fully addressed. Finally, the potential impact on background levels due to the introduction of the GEM stage should be discussed in greater depth, as this is a critical factor in low-background experiments.

Overall, this work presents a promising development in Micromegas-based TPCs for rare event searches, and the proposed approach could contribute to improved sensitivity in WIMP detection. However, additional discussion on long-term stability and potential drawbacks would enhance the completeness of the study.

Strengths:
1. **Clear Experimental Design:** The distinction between the preamplification factor and the GEM extra factor is well-motivated, addressing the practical limitations of voltage stability in a GEM-MM configuration.
2. **Comprehensive Data Acquisition:** Measurements at various pressures provide valuable insights into the scalability and practical performance of the setup under different experimental conditions.
3. **Application-Oriented Approach:** The study is clearly aimed at improving the TREX-DM experiment's sensitivity, with a focus on reducing the energy threshold, which aligns with the broader goal of enhancing low-mass WIMP detection.

Areas for Improvement:
1. **Target Audience:** The article appears to be primarily aimed at the astrophysics community. However, addressing a broader audience by including other Micromegas + TPC user communities, such as the muography community, would be beneficial. This could be mentioned in the first paragraph of Section 1, along with references to the use of Micromegas in geophysics, civil engineering, and archaeology.
2. **Limited Discussion on Systematic Errors:** While the results are presented with statistical confidence, there is little discussion on potential systematic uncertainties. For example, slight variations in voltage stability or differences in gas mixture purity could significantly impact gain factors.
3. **Insufficient Justification for Missing Data:** The absence of a preamplification factor at 1 bar due to noise issues is noted, but further elaboration on the specific noise sources and whether mitigation strategies were attempted would be beneficial.
4. **Lack of In-Depth Electron Transmission Analysis:** The study mentions that electron transmission effects were left for the full-scale setup, yet the border effects and lack of a field shaper could introduce artifacts that impact the interpretation of the GEM extra factor.
5. **Unexplained Anomalies in Gain Curves:** The non-parallel gain curves suggest complex interactions between the GEM and MM stages, possibly due to backflow effects, but no thorough hypothesis or further investigation is proposed.
6. **Limited Theoretical Comparison:** While experimental findings are well presented, additional theoretical discussion comparing observed gain trends with expected behavior from simulations or prior literature would strengthen the analysis.
7. **Scalability Concerns:** The reduction in maximum achievable voltage in the full-scale setup highlights an operational challenge when transitioning from small-scale to large-scale experiments. While this is acknowledged, further discussion on potential solutions or design modifications would be valuable.
8. **Replication Concerns:** The use of custom-made equipment, electronics, and data acquisition/analysis software (which are not provided or detailed) makes exact replication extremely difficult. Nevertheless, the basic operations, most of the equipment, and parameters are well described, allowing for a similar-but-not-identical replication.

References
1. Lázaro Roche I: A Compact Muon Tracker for Dynamic Tomography of Density Based on a Thin Time Projection Chamber with Micromegas Readout. *Particles*. 2021; **4** (3): 333-342 Publisher Full Text
2. Gómez H: Muon tomography using micromegas detectors: From Archaeology to nuclear safety applications. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*. 2019; **936**: 14-17 Publisher Full Text

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?

Partly

If applicable, is the statistical analysis and its interpretation appropriate?
I cannot comment. A qualified statistician is required.

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: -MPGD detectors, micromegas, time projection chambers, underground science, low background, dark matter

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 12 Mar 2025

Óscar Pérez Lázaro

Dear Reviewer,
We would like to thank you for your careful reading of our manuscript and for the constructive comments provided. Your suggestions have helped us improve both the clarity and robustness of our presentation. Below, we detail our responses to each of your points:

1. **Target Audience and Broader Community**

We agree with your suggestion regarding broadening the scope of our introduction. In the revised manuscript (Section 1, paragraph 1), we have now added references to recent muography studies and included a statement that highlights the relevance of these detectors not only to the astrophysics community but also to other Micromegas + TPC user communities, such as those in geophysics, civil engineering, and archaeology. This inclusive approach underscores the versatility of Micromegas-based detectors.

2. **Discussion of Systematic Errors**

In Section 3.1 (the paragraph beginning “Comparison of the position of the 5.9 keV peak in 55Fe calibration runs…”), we have clarified that the observed ±20% variation in the GEM extra factor arises from slight differences in the highest stable voltages (±5 V in V_mesh and V_GEM), as well as environmental variations (such as temperature and pressure) over several days and across different detectors. We now explicitly state that these variations inherently account for the systematic uncertainties in our measurements.

3. **Justification for Missing Data and Noise Issues**

Regarding the absence of the preamplification factor at 1 bar, we have added a comment in the Methods section to explain that the noise issues were traced back to fluctuations in the preamplifier and amplifier modules. We attempted several modifications (such as substituting alternative preamplifier and amplifier modules) but these efforts did not sufficiently reduce the noise. Since the main focus was on the GEM extra factor (which was successfully measured), we proceeded with our analysis while noting that further work on noise reduction is ongoing.

4. **Electron Transmission Analysis in the Small-Scale Set-up**

We acknowledge that the small-scale set-up was intended as an intermediate step. In the revised manuscript, we now include a statement clarifying that the small set-up was primarily used to demonstrate the feasibility of preamplification. We have done this by modifying paragraph 4 in Section 3.1: "Here, in all cases, E_drift = 100 V cm^{-1} bar^{-1} and E_transfer = 100 V cm^{-1} bar^{-1}, values which usually lie within the electron transmission plateau of the Micromegas. However, border effects cannot be excluded given the active area dimensions and the absence of a field shaper, so these values might not represent the optimal operating conditions. Nevertheless, given that the purpose of this set-up was just to prove the feasibility and potential of the combined GEM + MM system when installed in real experimental conditions in TREX-DM, detailed field optimizations were not the focus at this stage, and therefore, the in-depth study about the electron transmission (and gain curves) of the GEM + MM was left for the full-scale set-up in Subsection 3.2." This change highlights that while these values may not be fully optimized, the set-up serves its purpose as a feasibility study.

5. **Anomalies in Gain Curves and Future Systematic Studies**

We have noted that the non-parallel gain curves could be related to interactions between the GEM and Micromegas stages, possibly via backflow effects. To address this, we are in the process of constructing a dedicated set-up in Zaragoza (based on a small chamber similar to our current test system) in which we will perform systematic studies using UV laser calibration on a photocathode. Additionally, measurements with the GEM positioned at different distances relative to the Micromegas are planned to further elucidate these interactions. We have added a brief note to this effect in Section 3.2, acknowledging that a more detailed analysis will be the subject of future work.

6. **Limited Theoretical Comparison**

We appreciate the suggestion for a more detailed theoretical comparison. Although the current experimental results already provide strong evidence in support of our conclusions, we have now included a comment in Section 3.1 (the paragraph beginning "Comparison of the position…") about planned theoretical efforts to compare the observed gain trends with expectations from existing models. We believe that a deeper analysis will further enhance the understanding of the underlying processes and is underway. However, even if a complete understanding/modelling of the combined gain curves was not achieved, we still consider the experimental results presented in this article demonstrate the feasibility of preamplification in TREX-DM conditions and constitute an important result on its own.

7. **Scalability Concerns in the Full-Scale Set-up**

We recognize the challenge of achieving comparable voltage stability in the full-scale set-up, which is an ongoing area of development. To mitigate these issues, we are exploring the use of resistive Micromegas, which have demonstrated increased stability with respect to spark formation. This approach is expected to yield performance closer to that of the small-scale set-up. We have added a brief comment discussing these efforts in the last paragraph of Section 3.2.

8. **Replication Concerns and Transparency of Custom-Made Equipment**

We agree that the use of custom-made equipment and data acquisition software poses challenges for replication, which is sometimes due to certain aspects of our experimental

configuration needing very specific requirements (e.g., the number of channels and design constraints). To improve transparency, we have provided more information about the data taking and analysis processes in the small-scale set-up in last paragraph of Section 2.1, and of course we are open to providing more details and helping anyone with an interest in reproducing these results.
In summary, we appreciate your detailed comments and believe that the revisions strengthen our manuscript and provide a clearer context for our results. We believe that further improvements and additional studies will only enhance the robustness of our findings.
Thank you very much for your valuable input.
Sincerely,
The authors

Competing Interests: None

Reviewer Report 04 March 2025

https://doi.org/10.21956/openreseurope.20846.r51390

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David Attié
[1] Université Paris-Saclay, Gif-Sur-Yvette, France
[2] Université Paris-Saclay, Gif-Sur-Yvette, France

Dear authors,

* Summary

This article deals with a novel approach to enhance energy thresholds in low-background gaseous time projection chambers with high pressure gas mixture (up to 10 bar) using a Micromegas readout plane with an additional GEM preamplification stage.

The setup aims to improve the maximum effective gain for applications like dark matter searches (i.e. TREX-DM). The results indicate significant extra gain factors in various gas pressures, which help lower detection thresholds. A full-scale TREX-DM setup has been tested to replicate these findings effectively.

The article demonstrated the feasibility of an amplification scheme using Micromegas+GEM that should allow approaching the single-electron sensitivity in realistic TREX-DM implementations. This amplification scheme (GEM + MM combined) is being installed and commissioned at the TREX-DM experiment.

The improvement would open a new detection window at lower recoil energies that might lead to substantial improvement to low mass WIMPs.

* General comments:
- The article is written in a well-understandable English.
- The word Microbulk should be written with the first letter in upper case, same with Mylar, Kapton and X-ray.

*Minor corrections to be done:

- §1 Introduction
  > In 3rd paragraph, change "microbulk" to "Microbulk"
  > In 5th paragraph, change "mylar" to "Mylar", add a comma after "At each side," change kapton to Kapton and microbulk to Microbulk. Change "by means of a preamplification" to "by a preamplification" to avoid wordiness.
  > In 6th paragraph, change "microbulk" to "Microbulk" (x3) and "kapton" to "Kapton".
  > In 7th paragraph, change "microbulk" to "Microbulk" (x2). Remove the sentense : "This is also, to our knowledge, the first time that a combined GEM + MM readout is seriously considered for installation in a real experiment.". The hybrid (Microbulk + GEM) detector is used for the first time, but a combined GEM + MM have already been used in a real experiment (see Reference 1 and 2)
  > In 8th paragraph, change "microbulks" to "Microbulks".
- Caption Figure 2: change "microbulk" to "Microbulk".
- §2.1
  > In 1st paragraph, change "microbulk" to "Microbulk".
  > In 2nd paragraph, change "microbulk" to "Microbulk", "x-ray" to "X-ray".
  > In 3th paragraph, remove "in order" to avoir wordiness.
- §2.2
  > In 1st paragraph, change "8 l h-1 is set during 72 h in order to ensure..." to "8 L h-1 is set during 72 h to ensure...". Change "microbulk" to "Microbulk". Change "(256 en each direction)" in "(256 in each direction)". Change "x-ray" to "X-ray".
- §3.1
  > In 1st paragraph, change "...the GEM with respect to a fixed..." to "...the GEM regarding a fixed...".
  > In 5th paragraph, change "microbulk" to "Microbulk".
- §3.1
  > In 2nd paragraph, change "...but several hypothesis are..." to "...but several hypotheses are...".
  > In 4th paragraph, change "...such as CH4 or CF4 C4H10 due to their..." to "...such as CH4 or CF4 due to their...".
  > In 6th paragraph, change "...due to some backflow." to "...due to some ion backflow."
- §5 Conclusions
  > Change "...increase signal to noise ratio..." to "...increase signal-to-noise ratio...".
  > Change "microbulk" to "Microbulk" (2x).
  > Change "In this paper we..." to "In this paper, we...".
  > Change "...potentially down to unexplored region..." to "...potentially down to an unexplored region...".
- In References

> 5. Change "Development and performance of microbulk Micromegas detectors" to "Development and performance of Microbulk Micromegas detectors"

- The Compass experiment has already used an hybrid detector (GEM+Micromegas), but it was with bulk. This paper is the first time using and hybrid with Microbulk.

A minor revision of this paper has to be done, and comments/corrections have to be considered before indexed.

References

1. Neyret D, Abbon P, Anfreville M, Andrieux V, et al.: Aging effects in the COMPASS hybrid GEM-Micromegas pixelized detectors. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*. 2024; **1065**. Publisher Full Text
2. Neyret D, Anfreville M, Bedfer Y, Burtin E, et al.: New pixelized Micromegas detector for the COMPASS experiment. *Journal of Instrumentation*. 2009; **4** (12). Publisher Full Text

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Micromegas detector, TPC

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 12 Mar 2025

Óscar Pérez Lázaro

Dear Reviewer, Thank you very much for your careful review and constructive comments, they have helped to improve the quality of this article. We have revised the manuscript and incorporated all the suggested corrections. In particular:

- We have updated the terminology through the text (Microbulk, Mylar, Kapton, and X-ray) and we have addressed the typos and recommended stylistic corrections.
- In Section 1 (specifically, the 7th paragraph), we have removed the sentence "This is also, to our knowledge, the first time that a combined GEM + MM readout is seriously considered for installation in a real experiment." We now clarify that this hybrid configuration "...has been tested in the past [17] and successfully implemented in real experiments such as COMPASS [18, 19] using bulk technology, but this is the first time this is done with a Microbulk Micromegas, at high pressures, and in the context of low-background constraints." We were not aware that the COMPASS experiment upgrade in 2014-2015 had already used a combined GEM + MM readout (we thought GEMs and MMs had been used separately). We thank you for pointing out this important detail, and we have added the corresponding references.

Thank you again for your input and your time. Sincerely,
The Authors

Competing Interests: None