R&D for high pressure gas TPC readout with segmented Micromegas

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Abstract. In the framework of the R&D program for the ton scale phase of the EXO experiment, the possibility of using a xenon gas TPC with segmented Micromegas readout plane is under investigation. A small gas TPC has been built in order to study the energy and spatial resolution with Micromegas. Tests with P10 and xenon gas are under way. The apparatus and some preliminary results are presented.

1. Introduction
In the last 15 years, data from neutrino oscillation experiments, using solar, atmospheric, accelerator and reactor generated neutrinos, clearly indicate that the neutrinos have non zero masses. These experiments however can only determine differences of squared masses. The absolute mass scale can be determined by studying the kinematics in the weak decays of Tritium [1] [2] or, if the neutrino is a Majorana particle, by searching for neutrinoless double beta decay.

The Enriched Xenon Observatory (EXO) [3] is an experiment searching for the double beta decay of $^{136}$Xe. This isotope should decay through allowed double beta with the emission of two neutrinos to $^{136}$Ba, though past experiments have only placed limits on the half-life [4]. Observation of the 2$\nu$ mode is interesting for nuclear theory, but does not provide information about neutrinos. In contrast, neutrinoless double beta decay implies a Majorana nature of the neutrino and the rate of this process is proportional to the square value of the effective neutrino mass [5]. The study of 0$\nu\beta\beta$ may shed light on the absolute mass value, hierarchy and nature (Dirac-Majorana) of these amazing particles.

The first phase of EXO (EXO-200) is already running with a liquid TPC filled with 200 kg of pure xenon. Meanwhile a strong R&D program for a ton scale up-grade (EXO-full) of the system is pursued by the collaboration. Both liquid and gas option are under investigation.

A gas TPC implies a less compact apparatus, but electron tracks can well be visualized and identified, at pressures up to 5-10 bar, as demonstrated int the Gotthard TPC [6] and the MUNU TPC [7] [8]. Double beta decay events can be identified by using their topology: a candidate appears as a single track, with increased ionization at both ends. This may lead to a substantial background suppression. Moreover a gas apparatus allows the use novel sensors such as GEM or Micromegas for collecting charge and this should lead to a better spatial and energy resolution and an increased reliability.
Figure 1. (a) The 10 cm active area of the Bern Micromegas. Pixels are visible. (b) A detail of the grid. (c)-(d) The electrical layout of X and Y strips connection.

2. Bern mini-TPC setup
The Micromegas detector [9] is a fast gaseous detectors using a micro-mesh electrode separating the drift area from the amplification gap.

In order to study the adequacy of the Micromegas for double beta decay search, a mini-TPC apparatus (mTPC in the following) has been built at LHEP. Tests are performed using a Micromegas with a segmented anode plane built at CERN using photolithography by R. De Oliveira’s group [10]. The anode plane consists in a matrix of 2.1x2.1 mm pixels on a PCB board connected diagonally in the back using connecting vias. These pixels form interlaced X and Y strips with a pitch of 3.113 mm. There are 31 X and 30 Y strips, for a total useful diameter of 10 cm. Photo-resist pillars of 500 µm diameter and 256 µm height are placed off center on each pixel. They maintain the proper gap with the grid which is made of woven stainless steel wire of 18 µm diameter. A grounded guard ring surrounds the pixel matrix and provides a very uniform electric field on the edge of the detector.

The Micromegas is placed in a vessel at the end of 18 cm drift volume delimited by field shaping rings ad a cathode. Each strip is connected, using flat cables, to current preamplifier, developed at the LHEP institute, and sampled at 62.5 MHz by a 12 bit VME based Flash ADC. The grid is also sampled at the same speed.

The gas is constantly being recirculated through an Oxysorb filter and a cold trap, to remove oxygen, water and other contaminants. Moreover a Residual Gas Analyzer (RGA) allows to monitor the gas quality and its composition. A muon veto system is used to select or reject cosmic muons.
3. Muon tracks and gain factor
Preliminary tests have been performed filling the mTPC vessel with P10 (Ar(90 %)-CH$_4$(10 %)) at pressures ranging from 1 to 5 bar and looking at the ionization tracks generated by the cosmic muons. Data with a mixture of Xe (98%) and CF$_4$(2%) have been taken as well.

All the ADC channels have been calibrated. The raw current signals (fig. 3a) are integrated to get the charge (fig. 3b) then the noise level is evaluated (fig. 3c) and subtracted from the signal (fig. 3d). Finally the total charge deposited on each strip is estimated. The resulting data are organized in two bi-dimensional histograms that represent the projection of a track in the X-Z plane and the Y-Z plane where the Z axis is defined as the drift field direction. As shown in figure 4, very nice tracks in P10 up to 5 bar, and good tracks in xenon have been obtained. The analysis is still in progress, but one can readily state that the spatial resolution in X and Z is better than 2-3 mm.

To determine the gain factor of the Micromegas a software has been developed. The algorithm scans the bi-dimensional histograms and extracts the length of the tracks, the total collected charge, and then the dQ/dx. Simulations of the distribution for the muon dQ/dx in P10 and Xe-CF$_4$ have been performed with the HEED package [11]. Figure 5 shows one example of the simulated and experimental distribution of dQ/dx in which only tracks longer than 10 cm have been selected. The experimental distribution is fitted with a Landau function and the most probable value (MPV) is extracted from the fit. The ratio between the measured value and the simulated one gives the gain factor for a fixed amplification voltage and pressure. Data from Xe-CF$_4$ runs at the pressure of 1 and 2 bar have been analyzed.

4. Results
In figure 6, our results in Xe-CF$_4$ are compared with the previous one obtained with a 225µm amplification gap Micromegas and a non-segmented anode plane [12]. We were not able to reach the same amplification because discharges occur. The two experimental points correspond to a gain factor $G = 1674$ at 785V grid voltage and 1 bar of pressure and $G = 700$ at 1167V and 2 bars of pressure. They represent the highest achievable value for the gain before discharges developed between grid and pixels. The hypothesis is that the amplification gap is not large enough to allow the development of the shower and increasing the grid voltage induces the breakdown.

As the electron shower grows exponentially along the direction of the amplification field, a wider gap should lead to a better gain factor at fixed grid voltage. Two new Micromegas with gap of 320µm and 384µm respectively, are under construction at CERN and will be tested soon in Bern.
Figure 3. The four histograms show the steps of the signal treatment. The average noise level is evaluated from a Gaussian fit.

Figure 4. Left: track in P10 for a muon that cross the entire volume of the mTPC as it has been reconstructed by our software. Right: track in Xe-CF$_4$ at 2 bar. The Z distance is obtained multiplying the drift time and the electron drift velocity for the specific gas mixture, pressure and drift field.
Figure 5. On the left the simulated $dQ/dx$ distribution for muon in Xe-CF$_4$. On the right the measured distribution for one Xe-CF$_4$ run.

5. Prospectives

To complete the setup, a UV-light detector is under construction as well. It is well known that the spectrum of the scintillation light peaks around 174 nm in xenon. Scintillation and ionization are anti-correlated in Xe, the collection of the light as well as the charge, could provide a better energy resolution and a $t_0$ reference for the drift time.

We believe it is efficient in a large size TPC, to first catch the UV light in a light guide and then to convert it to visible using a wavelength shifter, finally detecting the visible light with sensors directly coupled on the guide.

The light guide must be relatively transparent to UV, which led us to chose polystyrene. Tetraphenylbutadiene (TPB) appears adequate as wavelength shifter [13] [14]. A large conversion ratio should be achieved with a 3 mm thick guide doped with 2% TPB per weight. The emission spectrum of TPB peaks around 440 nm which is optimal for photomultipliers and for solid state devices like Si photomultipliers (SiPM). The inner side of the TPC will be covered with TPB doped light guides attached to the field shaping rings. This scheme allows to collect UV photons over a large area in the TPC with a limited number of sensors. Si photomultipliers have been chosen as light sensors. These compact devices can be couple directly on the light guide inside the vessel and no light feed-troughs is needed to carry the light out of the vessel.

A bulk piece of scintillator consisting in TPB doped polystyrene has been produced by A. Olshevskiy and I. Nemchenok group at JINR Dubna. It has been already cut in slabs with dimensions 200x10x30 then polished. On one side they will be equipped with 3x3 mm SiPM which we have procured from JINR as well. These sensors are micro-pixel avalanche photo diodes operated in Geiger mode where each pixel acts as a photon counter and outputs a macroscopic current signal. Photons are counted by summing the signals arriving in coincidence from all pixels. The outputs of the SiPMs will be ganged together and the sum signal will be sampled at the same frequency as the TPC pixels.

Moreover for studying the energy resolution of the Micromegas at low energy level, the mTPC vessel will be provided with a mechanism that allows the insertion of a 5.9 KeV $^{55}$Fe X-ray source.
Figure 6. The Micromegas gain factor for Xe-CF$_4$ gas pressures ranging from 1 (starting from left) to 4 bars. Blue points are from ref [12], red points are our experimental results.

6. Conclusion
Xenon gas TPC with segmented Micromegas read-out plane could represent an interesting alternative for the EXO-full experiment. A strong R&D program is carried on by the Bern EXO group at LEHP using the mTPC setup. Encouraging result have been achieved with P10 up to 5 bars, and Xe-CF$_4$ up to 2 bars. New wider gap Micromegas, UV light system and radioactive source insertion mechanism will be available soon making the system complete and ready for detailed studies.

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