The Gotthard and MUNU TPCs: from the past to the future?

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Abstract. The performance of two similar gas TPCs used in past low energy particle physics experiments are briefly described. The first was installed in the Gotthard underground laboratory to search for the neutrinoless double beta decay of $^{136}$Xe. The second, MUNU, was operated near the Bugey nuclear reactor to study $\nu_e e^- \rightarrow \nu_e e^-$ scattering. The advantages of the design are presented, along with the limitations. Ideas to improve the performance, for future experiments in low energy, low rate, particle physics are presented. The emphasis is put on the search for the neutrinoless double beta decay of $^{136}$Xe.

1. Introduction

Gas TPCs have turned out to be very useful tools in low energy, rare event, particle physics. Among these are the Gotthard TPC, used for the search of the neutrinoless double beta decay of $^{136}$Xe, and MUNU, operated near the Bugey nuclear reactor to study $\nu_e e^- \rightarrow \nu_e e^-$ scattering. From the experience gained in the operation of these detectors, modifications are proposed in the following. They should lead to enhanced performances of TPCs in future experiments, achieving a better energy resolution and a better background suppression thanks to a better event signature. The emphasis is put on the search for neutrinoless double beta decay in $^{136}$Xe. In that case good energy resolution is essential to distinguish neutrinoless double beta decay from the allowed two neutrino one. These remarks are part of the thinking going on within the EXO collaboration [1] towards a search of this decay using a gas TPC, as an alternative to the baseline option with a liquid xenon TPC. They complement the presentation of D. Sinclair in these proceedings, where ion tagging is discussed. Similar ideas could however also apply to a next generation gas TPC for the study of low energy solar neutrinos in a TPC filled with CF$_4$ [2].

1.1. The Gotthard TPC

The Gotthard TPC [3] was installed in the Gotthard underground laboratory. It was contained in a copper vessel surrounded by a lead shielding (fig. 1). It was filled with xenon gas enriched to 68 % in $^{136}$Xe and 5 % CH$_4$ as a quencher. The TPC was operated at a pressure of 5 bar and had a fiducial volume of 180 l (5.3 kg of xenon). The fiducial volume was delimited by a cathode at the bottom, and a grid at the top. The charge was amplified behind the grid on an anode plane made from 20 $\mu$m thick wires with a 4.95 mm spacing, separated by potential wires. The anode signal was used to measure the total charge deposited in the fiducial volume, from which the energy is reconstructed. A pick-up plane having perpendicular x and y strip with
Figure 1. Left: the Gotthard TPC inside its lead shielding; right: x-z and y-z projections, the anode signal, as well as the reconstructed x-y projection, of a double beta decay candidate event.

3.95 mm pitch, placed behind the grid, measured the induced signal. With that information, combined with the z coordinate reconstructed from the drift time, the x-z and y-z projections of events were obtained. A good double beta decay candidate is a single continuous track within a radial fiducial volume with enhanced energy deposition at both ends. An example is shown in fig. 1. The energy calibration and the resolution were measured using radioactive sources. The double escape peak of the 2614 keV line in $^{208}$Tl was particularly useful. Extrapolating with the square root of the energy, an energy resolution of $\sigma(E)/E = 2.7\%$ was determined at 2.48 MeV, the energy $Q_0$ released in the decay. This is an average over the drift depth of the TPC, since no absolute z coordinate was available. No correction for charge losses along the drift path could be applied. Using $^{210}$Po $\alpha$ decays on the cathode, with fixed z, an energy resolution of $\sigma(E)/E = 1.1\%$ at 2.48 MeV was reconstructed, indicative of what can be achieved.

The experiment found no excess of events above background around $Q_0$, within energy resolution, and a limit of $T_{1/2}^{0\nu} > 4.4 \times 10^{23}$ yr was derived for neutrinoless double beta decay.

1.2. The MUNU TPC
The MUNU TPC [4] was inspired from the Gotthard one. It retained the same structure with, however, a larger fiducial volume (1000 l, fig. 2). It was filled with CF$_4$ at 3 bar for most measurements. CF$_4$ has a relatively low Z, meaning reduced multiple scattering. The TPC was contained in an acrylic vessel, immersed in a tank filled with liquid scintillator and viewed by photomultipliers. The scintillator served as a cosmics veto and as an anti-Compton detector. It was very useful in further constraining the background. An other advantage of MUNU over the Gotthard TPC was the read-out electronics, which brought a better spatial resolution.

Single electron candidate events were single continuous tracks within a fiducial radius, with increased energy deposition at one end. An example is shown in fig. 2. An excess of electrons from the reactor was found, in agreement within uncertainties with predictions of the standard model. An upper limit of $\mu_\nu < 9 \times 10^{-11} \mu_B$ on the magnetic moment of the neutrino was derived.
Figure 2. Left: The MUNU TPC; right: the x-z and y-z projections of a single electron track.

2. Possible improvements
To go to larger, more sensitive gas TPCs, improvements are required. Here are some ideas:

- A better reliability is required. The anodes wires were a problem. Here it is proposed to replace the anode plane and the grid by a Micromegas pattern [5].
- An absolute z-determination is necessary. This can be achieved by measuring the primary scintillation light, providing an absolute reference for the drift time and thus the z coordinate. This would help in correcting for the charge losses along the drift, and lead to an improved energy resolution. Moreover it would allow to define a fiducial cut in z, not only a radial one as in the Gotthard TPC and in MUNU. It would make possible a 3-D fiducial cut, eliminating entirely $\alpha$ and $\beta$ backgrounds from the walls, which are generally found to be significantly dirtier than the detector medium.
- A better spatial resolution is necessary. In the Gotthard TPC, and even in MUNU, the spatial resolution was not limited by diffusion, lateral or longitudinal, the ultimate limitation, but by electronic noise problems and by the granularity. Segmented Micromegas [6] could bring a substantial improvement. Improved spatial resolution would allow a better event selection, primarily by a better identification of the increased ionization at the end of an electron track.

3. Micromegas with xenon
In Neuchâtel and in Bern we have tested Micromegas read-out patterns with xenon gas using a small TPC [7]. The drift volume has a diameter of 10 cm and a length of 20 cm. The compact Micromegas consists of an anode and a grid, compacted “two in one” and separated with cylindrical pin spacers. The anode is a plain copper plated board with 9 cm of diameter. Kapton spacers with 250 $\mu$m diameter by 100 $\mu$m height or more and placed every 1 mm, are laid on it by conventional lithography. The height defines the amplification gap size. The grid is made of stainless steel wires, with 20 $\mu$m of diameter, woven with a pitch of 53 $\mu$m. It was tensioned delicately and glued with a thin glue layer to the outer part of the anode. The grid is pressed against the spacers.
No amplification sufficient to do tracking was obtained in pure xenon. It was found however that an addition of CF$_4$, even minute, gives a significant improvement. CF$_4$ was chosen as an additive because it does not absorb light. Measured gains and FWHM energy resolution at 5.5 keV versus grid voltage with a 100 $\mu$m gap at atmospheric pressure are shown in fig. 3. The Xe(98 %)CF$_4$(2 %) mixture appears particularly attractive.

![Figure 3](image)

**Figure 3.** Left: gain obtained with a Micromegas with 100 $\mu$m gap at atmospheric pressure for various gas mixtures in function of the grid voltage; right: gain at various pressures (bar) for 75 $\mu$m (▲) and 225 $\mu$m (★) gaps in Ar(90 %)CH$_4$(10 %).

Also it was shown that it is possible to increase the pressure to several bars if the Micromegas gap is increased as well. Gains in Ar(90 %)CH$_4$(10 %) are shown in fig. 3. The Micromegas with 225 $\mu$m gap was also successfully operated in Xe(98 %)CF$_4$(2 %) at pressures up to 4 bar. Gains of the order of $10^3$ were comfortably achieved at 4 bar. Clearly operation at 5-10 bar is possible.

4. Segmented Micromegas

Using photolithographic techniques it is possible to produce segmented Micromegas with a great flexibility in the geometry [6]. The anode is subdivided in pixels, which are read out individually or, connected together in various patterns, in groups. The grid can be segmented as well, in a coarser manner. The grid signal provides additional spatial information allowing to remove ambiguities. Fine granularity can be envisioned, with correspondingly good spatial resolution.

5. The primary scintillation light

Xenon, argon and CF$_4$ are known to be good scintillators. Xenon has a broad emission spectrum centered around 175 nm [8]. Several wavelength shifters can bring it to visible blue light. TPB, for instance, has been reported to have a fluorescence yield as large as 40 % [9]. TPB can be doped to polystyrene which can be evaporated to form thin films on light guides. In these impinging UV light will be shifted to blue light, a large part of which being trapped by total reflection, and reaching the end with good efficiency. There, it can be detected, for instance with photomultipliers.
6. A large gas TPC concept

All this leads to a large gas TPC for the search of double beta decay in $^{136}$Xe having the general structure depicted in figure 4. The central TPC has a Micromegas read-out system to measure the ionization charge with optimal spatial resolution. It is filled with a mixture of Xe ($98\%$)CF$_4$ ($2\%$) at 5-10 bar. This gas mixture should be transparent to xenon’s UV primary scintillation light. The primary xenon scintillation light is shifted to the blue in the TPB doped light guides and detected in photomultipliers. The central TPC vessel is immersed in a liquid scintillator anti-Compton detector, which is also efficient at detecting the annihilation gamma rays from positrons. This allows to suppress the background from $e^+e^-$ pairs, which exhibit the same topology as double beta events.

![Figure 4. A possible layout for a gas TPC to search for double beta decay in $^{136}$Xe, with an anti-Compton and a read-out system for the primary xenon scintillation light.](image)

All this, along with an installment deep underground and a careful selection of clean materials for the construction of the detector, should ensure a very high background suppression. With the dimensions given in the figure, masses of order 1 t can be achieved. However, R&D is necessary on some points to entirely demonstrate the feasibility and optimize the design.

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