Cryogenic gaseous photomultipliers and liquid hole-multipliers: advances in THGEM-based sensors for future noble-liquid TPCs

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Abstract. Dual-phase noble-liquid TPCs are presently the most sensitive instruments for direct dark matter detection. Scaling up existing ton-scale designs to the multi-ton regime may prove to be technologically challenging. This includes both large-area coverage with affordable high-QE UV-photon detectors, and maintaining high precision in measuring the charge and light signals of rare events with keV-scale energy depositions. We present our recent advances in two complementary approaches to these problems: large-area cryogenic gaseous photomultipliers (GPM) for UV-photon detection, and liquid-hole multipliers (LHM) that provide electroluminescence light in response to ionization electrons and primary scintillation photons, using perforated electrodes immersed within the noble liquid. Results from a 10 cm diameter GPM coupled to a dual-phase liquid-xenon TPC demonstrate the feasibility of recording – for the first time – both primary (“S1”) and secondary (“S2”) scintillation signals, over a very broad dynamic range. The detector, comprising a triple-THGEM structure with CsI on the first element, has been operating stably at 180 K with gains larger than $10^5$; it provided high single-photon detection efficiency – in the presence of massive alpha-particle induced S2 signals; S1 scintillation signals were recorded with time resolutions of 1.2 ns (RMS). Results with the LHM operated in liquid xenon yielded large photon gains, with a pulse-height resolution of 11% (RMS) for alpha-particle induced S2 signals. The detector response was stable over several months. The response of the S2 signals to rapid changes in pressure lead to the conclusion that the underlying mechanism for S2 light is electroluminescence in xenon bubbles trapped below the immersed THGEM electrode. Both studies have the potential of paving the way towards new designs of dual- and single-phase noble-liquid TPCs that could simplify the conception of future multi-ton detectors of dark matter and other rare events.

1. Introduction
Noble-liquid detectors used in dark matter searches and neutrino physics experiments are ever increasing in size and complexity. In particular, dual-phase noble-liquid time projection chambers (TPCs) [1-3], presently leading the effort for direct dark matter detection, are now entering the ton-scale regime with XENON1T [4] under construction at LNGS and ArDM [5] undergoing commissioning at LSC. Other ton-scale programs for direct dark matter detection with dual-phase
liquid xenon (LXe) and liquid argon (LAr) TPCs include LZ [6], PandaX [7] and DarkSide G2 [8]. These detectors comprise a large volume of liquid target (liquid xenon, LXe or liquid argon, LAr), in equilibrium with its vapor phase. Radiation interactions within the liquid lead to a prompt scintillation signal (“S1”). Ionization electrons liberated at the site of interaction drift towards the liquid surface; they are extracted into the gas phase, inducing, through electroluminescence, a delayed scintillation signal (“S2”) - proportional to the number of extracted electrons. Both S1 and S2 signals are usually recorded by top and bottom arrays of vacuum photomultiplier tubes (PMT). S1 usually defines the detection threshold; S1 and S2 are used to estimate the deposited energy and provide the 3D event localization. The ratio S2/S1 permits gamma background suppression (in LXe); in LAr detectors this is done by pulse-shape analysis.

The next step in the evolution of dual-phase TPCs will take them in the 2020s into the multi-ton regime with programs such as DARWIN [9], where they will probe the WIMP mass-cross section parameter space down to the region where irreducible neutrino background dominates. The realization of multi-ton dual-phase noble-liquid TPCs involves technological challenges that go beyond a simple scale-up of existing ton-scale designs. Among these challenges are the need to cover very large areas with affordable high-QE, low-radioactivity photon detectors (possibly in ~4π configuration), and the requirement for maintaining high precision in measuring the charge and light signals of keV-scale events, over a few-meter diameter TPC. In what follows we discuss our recent advances in two complementary approaches to these challenges: large-area cryogenic gaseous photomultipliers (GPM) for UV-photon detection, and liquid hole-multipliers (LHM), first suggested in [10], in which scintillation light is produced in perforated electrodes (e.g. THGEMs or GEMs) immersed within the noble liquid.

GPMs are high-gain gaseous detectors, in which incoming photons release photoelectrons from a high-QE photocathode; these are subsequently focused into a region of a strong electric field, where they undergo avalanche multiplication, enabling high single-photon detection and localization capabilities [11]. GPMs comprising a reflective UV-sensitive cesium iodide (CsI) photocathode [12] coupled to either wire chambers [13] or cascaded gas electron multipliers (GEM [14, 15]), have been successfully employed in room temperature particle physics experiments as RICH devices [13, 15-17]. An extensive R&D has been done on CsI-coated Thick-GEM (THGEM) GPMs [18-22], in particular for the COMPASS experiment [23,24].

In the context of dark matter detection, cryogenic GPMs [25] may allow for large-area coverage with high detection efficiency and high filling factor, potentially at significantly lower cost than PMTs and with a similar level of radio-purity. In dual-phase TPCs, GPMs with reflective CsI photocathodes may serve as the top array of photon sensors. With the possibility to segment their readout to small pixels, they can allow for an improved position reconstruction capability, with potential benefits in calibration and background rejection. Furthermore, GPMs with a semi-transparent photocathode may be mounted on the TPC wall (behind the field-shaping rings) to allow for close-to 4π coverage, with a potentially large increase in the detector sensitivity to low-energy depositions, and hence low-mass WIMPs.

A primary concern in scaling up dual-phase TPCs to the multi-ton regime is the requirement to keep the liquid-gas interface completely parallel to the two meshes bounding it from above and below across several meters. Especially for LXe TPCs, this requirement is essential for maintaining a high level of background discrimination capability. A possible solution to this problem may be to devise a single-phase liquid-only TPC, in which the charge signal (S2) is produced within the liquid by immersed electrodes rather than in the vapor phase. While other groups have investigated the feasibility of this idea by using thin wires [26, 27], we have chosen to focus on immersed liquid hole-multipliers (LHM) [10] (e.g. THGEMs or GEMs). Preliminary
results with a THGEM immersed in LXe were highly encouraging, with surprisingly large light gains, proportional to the THGEM field [28].

In this work we summarize our recent results in operating a 10 cm diameter, triple-THGEM cryogenic GPM prototype with a reflective CsI photocathode, coupled through a UV window to a small dual-phase LXe TPC. These results represent the first demonstration of the ability of such a detector to record both single photons and massive S2 signals in the same operating conditions. We also summarize our recent advances with the LHM concept, including a surprising new understanding of its underlying electroluminescence mechanism. Detailed reports about both studies can be found in [29] and [30].

2. Cryogenic gaseous photomultipliers

The experiments were conducted using the Weizmann Institute Liquid Xenon (WILiX) setup, described in detail in [27]. The cryostat comprises an inner vacuum-insulated LXe-filled chamber which housed, for the GPM experiment, a small dual-phase TPC at its center. Throughout the GPM experiments the cold finger condensing the xenon vapor was kept at 170 K, with the xenon gas pressure fixed at 1.8 bar; xenon gas was continuously recirculated at 3 slpm through an SAES hot getter for purification.

The TPC is schematically shown in figure 1 (a). It is comprised of two electro-formed Cu meshes set 5 mm apart, serving as the anode and gate and bounding the liquid-gas interface from above and below, respectively. A stainless steel disc, serving simultaneously as the TPC cathode and a spectroscopic alpha particle source (241Am with an activity of 80 Bq), was held 5 mm below the gate mesh. The TPC voltages were set to create a drift field of 1 kV/cm between the source and gate and ~10 kV/cm between the gate and anode. Alpha emissions from the source into the liquid resulted in prompt S1 light signals, followed by secondary S2 signals appearing ~2.4 μs later. A 1” square PMT (Hamamatsu R8520-06-Al), located 3.5 cm below the top surface of the source, was used to record reflected S1 and S2 photons.

The GPM assembly (figure 1 b) was installed above a fused silica window. It comprised a cascaded structure of three THGEMs held 2 mm apart, with an active diameter of 100 mm. Each consisted of a 0.4 mm thick FR4 plate, Cu-clad on both sides with an hexagonal pattern of 0.4 mm diameter holes surrounded by 50 μm etched rims, with 0.8 mm between their centers. CsI deposition on the first THGEM was carried out in a dedicated evaporation setup, following...
standard procedures [12]. The deposited layer was ~300 nm thick with a nominal QE of ~20-25% at 175 nm. The signals were recorded from the whole, un-segmented readout plane, with a charge-sensitive preamplifier located outside the system. An electro-formed Cu mesh with 85% transparency was set 3 mm below the first THGEM and kept at the same potential as its CsI-coated face (to optimize the extraction of photoelectrons from the photocathode). The GPM working gas was Ne/CH$_4$ chosen because it provides both a high gas gain at relatively low voltages [31] and high photoelectron extraction efficiencies [20, 32]. For the initial experiments we used Ne/CH$_4$(5%) and Ne/CH$_4$(20%). Most of the data were taken at a pressure of 0.7 bar with the GPM gas at 180 K. Typical S1 and S2 signals of both the GPM and the reference PMT are shown in figure 2.

Figure 2: Typical alpha-particle induced S1 and S2 signals recorded by the PMT and GPM (shown in figure 1b). The GPM, in this case, was operated with Ne/CH$_4$(5%) at 0.7 bar and 180 K, at a gain of ~$1\times10^5$. The GPM signal was shaped using a timing filter amplifier.

Figure 3 shows the measured GPM gain curves for Ne/CH$_4$(5%) and Ne/CH$_4$(20%). The voltage division was asymmetric in both cases, with the highest voltage across THGEM1 to maximize the photoelectron extraction efficiency [20] and improve the overall stability. For both gas mixtures the maximal gain was well above $10^5$, assuring high single-photon detection efficiency. At a gain of $10^5$ in Ne/CH$_4$(5%) the operation with alpha-particles at 40 Hz, yielding very large S2 pulses, was fully stable - indicating a discharge probability below $3\times10^{-6}$. To the best of our knowledge, this is the first time a cryogenic GPM was shown to record S1 and S2 signals from a LXe dual-phase TPC and operate stably over such a broad dynamic range - from one to several thousand photoelectrons.
Gain curves of the GPM shown in figure 1b, with Ne/CH$_4$(5%) and Ne/CH$_4$(20%) at 180 K and 0.7 bar, vs. the equal voltages across the second and third stages. The voltage values across the first THGEM, $\Delta V_1$, are given in the inset; the induction and transfer fields were 1 kV/cm in all cases.

S1 and S2 spectra are shown in figure 4. The estimated number of photoelectrons in the GPM is a few tens for S1 and a few thousands for S2 signals. For S1 the RMS resolution is $\sigma/E \sim 11\%$ (by fitting a Gaussian to the entire S1 peak). For S2, the asymmetric shape of the spectrum reflects the coincidence of alpha and 59.5 keV gamma emissions from the source, and a Gaussian fit to the left side of the peak gives $\sigma/E \sim 8.7\%$. The S2 resolution recorded here is roughly the same as that obtained in XENON100 ($\sigma/E=10.0\pm1.5\%$) with PMTs, for a similar number of ionization electrons entering the gas phase [33]. The ratio of alpha and 59.5 keV peaks (~4) is consistent with the vastly different charge yields of ionization electrons from the tracks of an alpha particle and of a 60 keV electron [3].

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Figure 4: Pulse-height spectra recorded with the GPM in the setup shown in figure 1, with a spectroscopic $^{241}$Am source. Left – S1 spectrum; right – S2 spectrum. Note the 59.5 keV gamma peak and the asymmetric right side of the alpha-particle S2 peak, attributed to coincidence between alpha and gamma emissions. Data recorded with Ne/CH$_4$(5%) at 180 K and 0.7 bar with a GPM gain of $1\times10^5$.

Figure 5 (left) shows the PMT alpha-particle S1 signal and the corresponding GPM one (after the charge-sensitive preamplifier), with the trigger on the PMT signal. The ~200 ns delay in the GPM signal reflects the time lapse from photoelectron extraction to the collection of the avalanche electrons on the readout plane. The distribution of the time difference between the two
pulses (figure 5, right), defines the time resolution of the GPM (here – for a few dozen photoelectrons); it is \( \sim 1.2 \) ns.

**Figure 5:** Left: alpha-particle S1 signals recorded by the PMT and GPM. Right: PMT-GPM time-difference distribution. The RMS width, defining the GPM time resolution, is \( \sim 1.2 \) ns.

3. **Liquid hole-multipliers**

The preliminary results for alpha-induced secondary scintillation (“S2”) in a THGEM immersed in LXe were reported in [28]; they indicated a large light gain of a few hundred photons per ionization electron focused into the THGEM holes. However, the very low threshold field in the holes (a few kV/cm) required for the appearance of S2 signals led us to suspect that the scintillation mechanism was different than originally thought. Extensive investigations, described in detail in [30], confirmed the initial observations of steady-state S2 signals, but we now have the following understanding: the observed electroluminescence occurs in gas bubbles trapped below the THGEM electrode, rather than in the liquid itself. A schematic drawing of the experiment (installed in WILiX), in light of this new understanding, is shown in figure 6.

**Figure 6:** Schematic drawing of the LHM setup, including the (hypothesized) xenon gas bubbles trapped below the THGEM. Alpha-induced ionization electrons drift towards the THGEM electrode and are focused into its holes. The high field inside the holes drives them into the trapped gas bubbles underneath, where they produce the S2 light, through electroluminescence - recorded by the PMT.

Aside from the very low threshold field for scintillation (smaller by about two orders of magnitude compared to the values reported for thin wires immersed in LXe [26, 34, 35]), the most compelling evidence for bubbles is the response of the S2 signals to rapid changes in the system pressure. A rapid increase in pressure (induced by a step increase in the cold finger
temperature), results in the immediate disappearance of the S2 signals; the signals reappear either if the pressure is reduced back to its original value, or if the system is allowed to warm up until stabilizing at a higher steady-state temperature. Our interpretation is as follows. When the system is in thermodynamic steady state, bubbles are continuously formed on one or more ‘hot’ surfaces, and are subsequently trapped below the THGEM - allowing for the generation of electroluminescence signals in the sufficiently high THGEM field. A rapid pressure increase causes the bubbles to collapse; bubble formation stops because the temperature of the bubble-forming surfaces (which does not change sufficiently fast) is too low to allow bubbles to grow against the new, higher pressure. Bubble formation resumes when the temperature of these surfaces becomes high enough, resulting in the reappearance of S2.

During several months of experiments, S2 signals were always present when the system was in thermodynamic steady state (i.e., fixed temperature and pressure), appearing for \( \approx 99.5\% \) of the triggers on alpha-particle induced S1 - indicating a constant presence of bubbles below the THGEM electrode. The magnitude of S2 signals, shown in figure 7a, depended approximately linearly on the THGEM voltage; it remained practically unchanged during 3 months of measurements; surprisingly, no pressure-dependence was observed. The RMS width (\( \sigma/E \)) of the alpha-particle S2 in steady state conditions was \( \approx 20-25\% \) as a result of occasional S2 amplitude fluctuations. However, when the S2 signals reappeared (after gradual warming up of the system following an increase in pressure), they remained, for 1-2 hours, in a ‘super-stable’ state, in which their RMS resolution was \( \approx 11\% \), close to that of XENON100 for the same number of drifting electrons (\( \sigma/E=10.0\pm1.5\% \)) [33]. The spectrum of S2 signals in the ‘super-stable’ state is shown in figure 7b.

Assuming that the major contribution to S2 comes from light emitted at the bottom of the THGEM holes, we estimate that the light gain is a few tens of photons emitted into \( 4\pi \) per electron focused into the hole, for a THGEM voltage of 3 kV.

![Figure 7](image_url)

**Figure 7:** (a) S2 area (time integral of pulse) vs. the THGEM voltage, for a drift voltage of 50 V (corresponding to a drift field of \( \approx 0.2 \) kV/cm), taken at different dates over more than two months; note the surprising similarity between the results at 1.3 bar and 2.1 bar. (b) Alpha-particle S2 area distribution, right-fitted with a Gaussian. The low-energy tail on the left reflects the fact that the \(^{241}\)Am source used in these measurements was non-spectroscopic (unlike the one used in the GPM study). The RMS resolution is 11.1%, close to that of XENON100 for the same number of ionization electrons.
4. Summary and discussion

The present study provides a first proof-of-concept for using cryogenic GPMs as large-area detectors, capable of recording both S1 and S2 signals from a LXe dual-phase TPC over a broad dynamic range. The demonstrated S2 energy resolution recorded by the GPM for alpha particles is similar to that obtained with XENON100 using PMTs for the same number of ionization electrons. The time resolution (here measured for pulses comprising a few dozen photoelectrons) is \(\sim 1.2\) ns, well within the requirements of direct dark-matter detection experiments. While the GPM single-photon detection efficiency was not measured directly in this experiment, based on the QE of CsI at 175 nm (25%), the geometry of the electrodes, the mesh transparency and the gas composition, we estimate it to be \(\sim 10\%\), in the present setup. This can be further increased to \(\sim 15\%\) by optimizing the detector parameters as discussed in [29]. Assuming a 90-95% filling factor of square GPM modules of a typical size of 30×30 cm\(^2\), the overall single-photon detection efficiency for an entire GPM array would be \(\sim 14\%\). We note that the GPM single-photon detection efficiency may be further enhanced by the addition of a semi-transparent CsI photocathode on the inner surface of the fused-silica window. This option, also important for 4\(\pi\) coverage of the TPC (figure 8a), is currently under investigation by our group. The GPM concept has been also investigated by us as a readout element for a LXe camera for combined fast-neutron and gamma imaging [36, 37].

Our recent advances in understanding the underlying mechanism for electroluminescence in a THGEM immersed in LXe, and in particular the identification of the ‘super-stable’ boiling regime with its accompanying high S2 RMS resolution, may open new possibilities for the design of future noble-liquid TPCs. An essential requirement for the successful implementation of this idea (the ‘bubble-assisted LHM’) is to devise a scheme in which bubbles are produced in a controllable manner. A successful outcome could lead to the conception of single-phase liquid-only TPC designs, in which ionization electrons drift down towards the bubble-assisted LHM (figure 8b). Photons could be recorded with pixilated GPM arrays underneath. Furthermore, coating the LHM top surface with CsI would allow for the detection of S1 photons as well as ionization electrons, as originally suggested in [10].

Although the present study focused on LXe, both the GPM and LHM concepts may be also considered for LAr TPCs. GPMs for LAr may be conceived with MgF\(_2\) windows for the direct detection of 128 nm photons (without wavelength shifters), relying on the high QE of CsI at this wavelength (>55% [12]). We note that the bubble-assisted electroluminescence identified in LXe may have also been responsible for previous observations in LAr with immersed THGEM [38] and GEM [39] electrodes. Besides dark matter searches, one may thus consider the use of bubble-assisted LHMs with GPM readout in LAr TPCs for neutrino oscillation experiments. More details can be found in [29, 30].
Figure 8: Possible TPC configurations employing GPMs and LHMs. (a) Dual-phase TPC with $4\pi$ GPM readout; the field shaping rings are spaced to allow photons to reach the wall GPMs. (b) Single-phase liquid-only TPC with inverted drift field, bubble-assisted LHM at its bottom and $4\pi$ GPM coverage.

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