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Optical readout of liquid argon ionisation

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Abstract Reading out the charge from a very large liquid argon detector, such as proposed for next generation proton decay and long baseline neutrino detectors, represents a significant challenge. Current proposals suggest using wires in the liquid or a two-phase approach that can provide some gain via amplification in the gas phase. We present here work on an alternative new approach in which the charge is read out by optical means following generation of electroluminescence, such as in a THGEM (Thick Gas Electron Multiplier) mounted within the liquid. This has the potential for significant advantages by providing both simpler readout electronics and significant charge gain, without the need for the complexities of dual phase operation. Tests with a silicon photomultiplier (SiPM) mounted above a THGEM, all submerged in liquid argon, have allowed first demonstration of the technique. Sensitivity to 5.9 keV ^{55}Fe gamma events was observed with an estimated gain of 150 photoelectrons per drifted electron. We review the concepts and results.

1. Introduction

The readout options currently being developed for liquid argon detectors can be divided as follows: (1) Single phase concepts in which readout occurs only in the liquid using either wires, such as in ICARUS [1], or via detection of the primary scintillation using photomultipliers, such as in the dark matter experiments DEAP/CLEAN [2]. The former technique provides essentially no internal gain, while the latter provides only very crude position information and no tracking. (2) Double phase concepts in which readout occurs in the gas phase following extraction of charge out of the liquid. Here, techniques studied include use of amplification of the charge with LEMs, GEMs, THGEMS or Micromegas plus readout with anode plane strips, or conversion to electroluminescence in the gas and readout by photomultipliers. An example of the former is used in the ArDM dark matter experiment, with LEMS [3], and of the latter is in WARP [4] - both dark matter experiments.

None of these concepts look ideal for scale-up to very large mass (>10ktons) for proton decay or long baseline neutrino physics. Here the requirement is for tracking capability with resolution of a few mm and homogeneous calorimetry, with modest gain (say ~x100), effective throughout the large volume, robust enough to stand underground installation over decades at reasonable cost. The

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development of new optical techniques attempts to address this. To produce a better way to readout charge in the liquid, with gain, noise and stability improved over that obtained with wires, and a better way to control the number of readout channels. The motivation recognises also particular challenges for two phase operation that would be best avoided if possible. For instance, the need for precise, long term, levelling of liquid argon over 100s m^2, the need for extreme cooling stability, for control of the liquid-gas interface, for a very high (~MV) cathode voltage to produce the necessary large drift distance, the need for a design that is not modular, and some complex engineering to allow support of the detector plane above the liquid but within the containment vessel [5].

An optical readout technique in single phase liquid, through making use of electroluminescence generation in the liquid, could solve many of these issues. It would allow modest gain to be produced without the need for the gas phase. This would also allow some degree of internal subdivision of the volume to reduce the requirement for long (>10m) drift distances and hence the complication of very large cathode voltages. This would also reduce the requirements for very high liquid argon purity, already difficult to achieve because the vessel is likely too large to be evacuated.

2. Optical readout concept and SiPDs

The concept under development by our groups to tackle this issue and described here, aims to produce a homogeneous tracking calorimeter based on planar, optical tracking readout with gain in single phase liquid. The particular concept adopted for proof of principle tests is to use THGEMs with a sparse distribution of holes mounted within the liquid argon and observed by cryogenic silicon photodiodes (SiPDs) also mounted in the liquid, positioned above the holes. This concept has been developed by picking the best in current relevant technology. A typical design considered would be to have 36 SiPDs per m^2 of THGEM plane in a 6 x 6 array of row and column readout. Planes of THGEMs could then be built up to reach 10s m^2 readout areas. The array of photosensors behind the THGEMS would be used to image the light signals using the conventional Anger Camera technique to do off-line imaging and track reconstruction, by reconstructing the centroid of the light emission in the XY plane, and using the electron drift velocity in the liquid to give the drift coordinate. Total decoupling of the optical readout from the electronics (that is the drifting charge transfer and readout) promises also superior noise performance. The significant reduction in complexity of this concept allows modular construction of large arrays with readout in any plane and any orientation, not just vertical.

Our concept builds on previous work with various collaborators developing liquid noble gas readout. Notable here is work on readout of charge using GEM structures in the saturated gas phase above liquid argon [6]. Here it was demonstrated with a test device with 1cm thick liquid argon, that charge can be extracted from the liquid phase into the gas and amplified with a triple GEM mounted above. Operation was achieved in single electron counting mode in the gain region from 6,000 to 40,000 with good stability. A parallel experiment using GEMs and Micromegas in liquid xenon was also able to achieve amplification in the gas phase of a two-phase xenon test device [7]. Here a gain of 500 was achieved at 171 K in 1450 Torr. In this case it was found that stability could not be achieved in pure cryogenic saturated xenon gas without the addition of a quench gas. Typically 2% Methane was added to the gas without apparent detrimental effect to charge transport in the liquid. Micromegas has also been successfully operated in various gases, including the negative ion gas CS_2 [8].

Building on these efforts, attempts have been made to obtain charge gain in the liquid using GEM or THGEM structures. However, stability is found to be very hard to obtain, particularly with liquid xenon, given the high electric fields required within the microstructures when using noble liquids. This has led to the alternative concept in which use is made of the potential secondary electroluminescence in the liquid that should be present in the THGEMs, even at lower fields where stability and freedom from breakdown should be more easily obtained. To investigate this requires precision photon detection in the liquid. In principle, PMTs could be used. However, it is important to understand the behaviour of light production generation in the THGEM holes. For this a new device has emerged that is ideal, the silicon photodiode, for instance as produced by Sensl Ltd. Such a device can be mounted above individual holes and in principle, with a suitable wavelength shifter, be used to study photon production. CCDs where also considered. However, one of the advantages of SiPDs is that the front end electronics and amplification can be positioned away from the sensor and so removed as a potential heat source. This is very difficult for CCDs where the electronics is integral to the chip.

SiPD devices are not specifically designed for cryogenic use, hence extensive studies have been undertaken by us to check operation, stability and gain characteristics at low temperarture [9]. The particular device used had pixel size of 20 μm with 848 cells and geometric efficiency of 43%. Our studies in cold saturated argon gas showed that the device has excellent characteristics at the required temperature of -196 ^{0}C, in fact showing improved gain of up to 3 x 10^6 and reduced dark count of a few 10s Hz, compared to >10^6 at room temperature. The photon detection efficiency was found to be 25% at 460 nm and 11% at 680 nm. Fig. 1 shows typical gain characteristics of the SiPD vs. low temperature. It can be seen from this that for a given bias voltage greater gains are achieved at liquid argon temperatures than at room temperature by a factor 2-5.

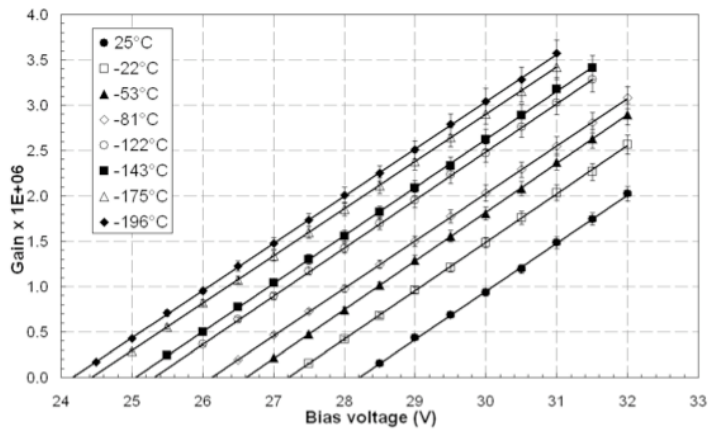

Figure 1 Typical gain characteristics of the Sensl SiPD vs. low temperature.

3. Optical readout test set-up

Based on the Sensl device, a liquid argon stand was constructed that allowed a 1 mm^2 SiPM device to be positioned directly above the centre of a 65 mm diameter THGEM. This was located above a 20 mm drift region defined by a woven steel cathode. Fig. 2 shows a schematic of the test set-up. Further details can be found in ref. [10]. The THGEM was manufactured in-house from a double faced copper clad FR-4 epoxy resin glass reinforced composite plate of thickness 1.5 mm, hole diameter 1 mm, pitch 1.5 mm. Only the central 45 mm diameter region of the THGEM was perforated. No dielectric rims were etched around the THGEM holes. On completion of CNC machining, the THGEM was immersed in 10 M nitric acid to smooth surface irregularities.

Considerable attention was paid to the purification of the liquid argon in the tests to achieve the required level of less than 30 ppb. N6 gaseous argon was first passed from its cylinder through a purification cartridge containing a 1200 g blend of powdered copper and phosphorous pentoxide to remove the bulk of oxygen and water respectively. The argon gas was then passed through a SAES getter at a flow rate of 5 L/min at 1.2 bar to remove oxygen and water to less than 1 ppb. To allow continued removal of impurities such as physisorbed water from within the target during operation, an additional purification cartridge was positioned at the base of the chamber directly below the target assembly. In addition to copper and phosphorus pentoxide, this cartridge contained molecular sieves to remove mineral oil, turbo and rotary pump oil.

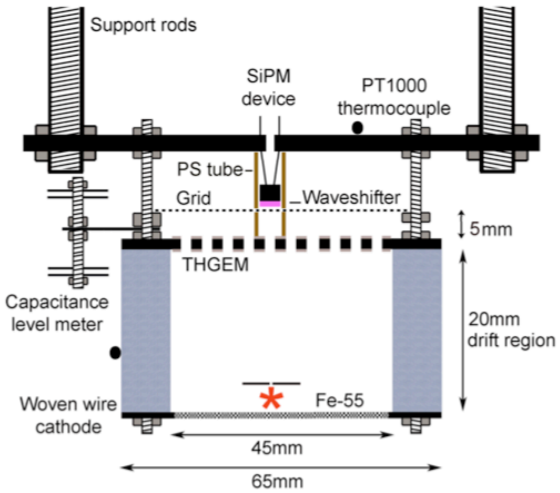

Figure 2 Internal assembly used to detect secondary scintillation in liquid argon.

As seen in Fig. 2 the THGEM was attached to the drift region below, and to the SiPM device above, using long polypropylene bolts. The SiPM device was shielded from the field within the THGEM by a grounded high optical transparency woven steel mesh grid, positioned between the THGEM and the SiPM device in order to deflect electrons passing through the THGEM holes back towards the THGEM top electrode, each hole acting as an independent amplifier. The transparency of the THGEM was 40%. In addition two 5 mm diameter polystyrene cylinders were fitted between the SiPM and the THGEM to isolate the SiPM device from background scintillation light from the argon target. A 50% concentration of the waveshifter tetraphenyl butadiene (TPB) in a mineral oil based diblock copolymer elastomer was applied to the SiPM face.

4. Readout results

The test rig of Fig. 2 was used to investigate the charge and optical response of the THGEM and the SiPD to interactions from ^{55}Fe x-rays in the liquid argon in various configurations. The charge signal, read from the top THGEM electrode, was decoupled from the high voltage line and passed through an Amptek A250 charge sensitive preamplifier and a shaping amplifier to an Acqiris PCI acquisition system, triggered through a discriminator unit. Tests were performed first with two phase argon to establish operation characteristics for the THGEM and SiPD in cold saturated gas above the liquid. Fig. 3 (left) shows an example charge spectrum of ^{55}Fe events taken from cold 1 bar gaseous argon in two phase mode. Here the THGEM was operated at 4.685 kV with a drift field in the liquid of 2.5 kV/cm and in the gas of 4.0 kV/cm. The gain in this test was 300. By adjusting the drift fields it was possible to check that the events were indeed from the ^{55}Fe source.

Turning to the SiPD, we show in Fig. 3 (right) the secondary photon spectrum from electroluminescence generated in the THGEM from the same source as recorded by the SiPD, using the same two phase set-up and the same drift voltages. The SiPM over-voltage was 1 V. Here again a clear ^{55}Fe spectrum is seen with escape peak below 3 keV and evidence for single photoelectron structure at low energy. The main peak was found to correspond to 86 photoelectrons. This demonstrates stable operation of the SiPD at the necessary cryogenic temperatures relevant to liquid argon. Again confirmation of the source detection comes from changing the drift fields and observing changes in the gain and position of the spectral peaks.

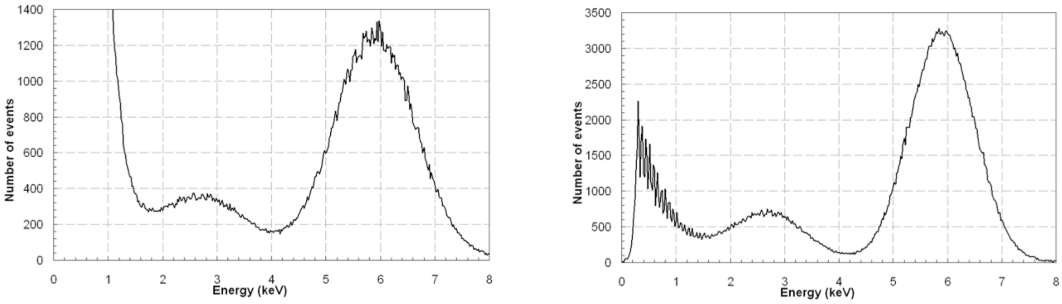

Figure 3 Spectral response from ^{55}Fe x-rays for operation in two phase liquid argon showing (left) charge readout from the THGEM and (right) optical readout of electroluminescence from the THGEM using the Sensl SiPD in the gas phase, all taken using the same drift voltages.

Operation in the two phase mode demonstrated also that the secondary scintillation is initiated in advance of the charge multiplication and consistently produces higher gain at comparable voltages.

The next, and most crucial, test was to increase the level of liquid in the apparatus to cover both the THGEM and SiPD and allow investigation in single phase liquid argon only. Study in this mode first demonstrated that generation of any measureable charge gain from the THGEM submerged in the liquid was not possible. However, as the voltage across the THGEM was raised above 8 kV scintillation light became clearly visible, yielding eventually an observable ^{55}Fe spectral peak. Fig. 4 (left) shows an example of this for a THGEM voltage of 10.15 kV with drift field in the liquid of 2.5 kV/cm. The peak here corresponds to 123 photoelectrons. As the voltage across the THGEM was increased the proportion of events containing discharge sparking also increased and this eventually limited the useful gain. To illustrate confirmation of the detection of the electroluminescence we show in Fig. 4 (right) the result of operation with the same parameters but with zero drift field in the liquid. As expected only noise from the SiPD is now observed, because charge from the signal events is no longer transported to the THGEM.

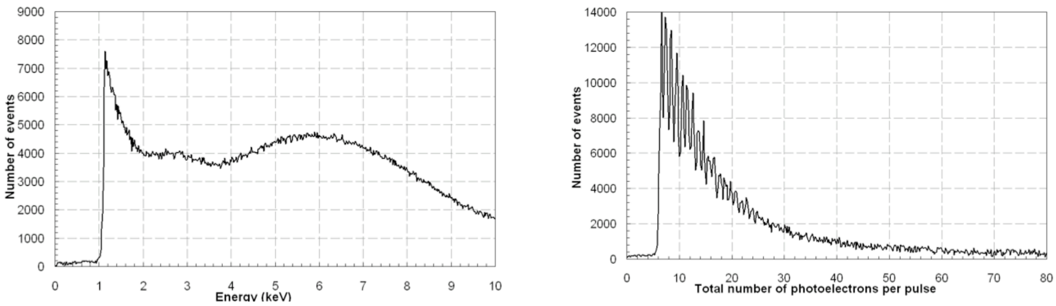

Figure 4 Spectral optical response to ^{55}Fe x-rays for operation in single phase liquid argon where the THGEM, with voltage of 10.15 kV, and SiPD, are submerged in the liquid for: (left) operation with liquid drift field of 2.5 kV and (right) zero drift field.

The results of Fig. 4 demonstrate for the first time the proof of principle that optical readout and gain in single phase liquid argon can be achieved in a stable configuration, at least on a small scale (further details are provided in [10]. The resolution for the optical readout shown at this stage is seen to be degraded somewhat compared to that of the cryogenic gas operation (see Fig. 2). There are several reasons for this, notably the 10μs integration time required to fully acquire the slow component time constant of 1590 ns. Since the software records all photoelectrons generated within this long time window the data will most likely contain in addition to an ^{55}Fe pulse, contributions from primary scintillation due to background interaction with liquid argon contained within the polystyrene tube, effects generated by the SiPM device, and also photons created due to sparking within the THGEM operating close to the breakdown threshold. However, overall, we can state that for a SiPM over-voltage of 1 V, a THGEM voltage of 9.91 kV, and a drift field of 2.5 kV/cm, a total of 62 +/- 20 photoelectrons were produced at the SiPM device per ^{55}Fe event, corresponding to an estimated gain of 150+/-66 photoelectrons per drifted electron.

5. Implications of single phase optical readout and alternative concepts

The new liquid argon detection technique described above opens great potential as a route to cost-effective, large volume, simultaneous tracking and calorimetry targets with excellent performance relevant to neutrino physics. The tests demonstrate that secondary scintillation in the liquid can clearly be observed by the SiPD-THGEM arrangement with gains at least in the region 100-200. At higher gains the resolution degrades in the current set-up. However, there are likely ways to mitigate against this with improved geometry, such as to reduce events from primary scintillation.

Nevertheless, there are issues to address, in particular to improve understanding of the gain vs. light characteristics of the THGEM holes. So far only one hole as been used. There are likely to be effects related to the quality of the manufacturing concerning the dependence on surface treatment in relation to high fields generated on any protrusions. It is also possible that corona discharge from local field instabilities caused by mechanical artifacts in the THGEM hole may be leading to positive photon feedback, resulting in premature breakdown and the narrow operating regime at high voltage. This issue is widely held to be a fundamental reason why significant charge gain has been unattainable using micropattern devices in liquid noble gases. Regarding SiPDs, several improvements are underway by manufacturers. Notably to improve dynamic range and produce larger area devices with more pixels.

The work with SiPDs suggests several routes toward scale-up arrays, for instance using fibre optics and/or the Anger camera technique discussed in Sec. 2. However, alternative optical readout ideas are also being investigated. One possibility is to use new UV sensitive integrated micromegas technology [11]. This detector consists of a CMOS imaging array, a gaseous-detector structure with a Micromegas layout and a UV-photon sensitive CsI reflective photocathode all monolithically integrated using simple post-processing steps. Typical imaging areas of 14 x 14 mm with 256 x 256 pixels have been produced, based on the InGrid technology and Timepix chip variant of the Medipix2 chip. The detector needs to be confirmed for operation in cryogenic liquids and looks costly for large areas.

Another possibility is to use Charge-Coupled Devices (CCDs) [12]. Recent breakthroughs in CCD development toward Charge-Coupled CMOS Pixel devices offer possibility of low noise, high QE and high speed (1-100 MFrames/sec). There is growth to larger area devices and smaller pixels (50 μm) and cryogenic use (e.g. for space). There are several variants, but the key features are: (a) collection of signal charge on a fully-depletable structure (PG or PPD) with large capacitance, (b) shield in-pixel electronics with a deep p-implant, (c) use of sense 'baseline' voltage on the gate of the submicron transistor having minimal capacitance, (d) transfer of the entire signal charge to this gate and sample again, *promptly*. Such devices might offer an effective way of imaging the light from THGEM holes in the gas or liquid as a cost effective way of reading out the light and performing tracking.

The CCD concept itself, essentially of imaging a gaseous TPC (Time Projection Chamber) using CCDs, has been studied for some years for dark matter experiments. For instance, in early work for the DRIFT experiment [13], and more recently by the DM-TPC collaboration [14]. Fig. 5 shows an example of an alpha particle track imaged optically from luminescence generated by a GEM in a TPC with 20 Torr Ar (90%) + CH_4 (10%) + TEA and recorded with a CCD from the DRIFT work [13].

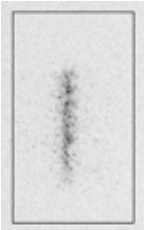

Figure 5 Example of an alpha particle track imaged optically from luminescence generated in a GEM and recorded with a CCD [13].

There are however several potential pitfalls to the CCD optical concept in scale-up operation for liquid argon. One issue is the need for VUV optics required to collect the light, including arrangement for the space required to mount the lenses. This may mean consideration is needed for use of MgF and/or wavelength shifters. Another issue is power consumption, particularly in the case of operation in liquid where it is vital to prevent evaporation. This arises because the CMOS electronics is integral to the CCD. Designs will likely need to minimize pixels numbers and power dissipation. The CCDs will need to be exceptionally fast also, to ensure allow measurement of the drift distance. Finally, recent work by Bondar et al. [15] with Geiger Mode APDs have also now demonstrated readout of secondary electroluminescence light from THGEMs in a two phase device, but achieving this without use of wavelength shifter. This was possible through use of the near infra-red emission, found with 20% photo-detection efficiency. An avalanche gain of 60 was achieved with 1.4 photoelectrons per electron, with ~180 p.e. recorded per 60 keV scintillation event (from an ^{241}Am source) in the liquid.

6. Conclusion

There is evidence now, at proof-of-principle level, that optical readout of secondary electroluminescence in liquid argon could provide an alternative to charge readout. This has the potential to provide the necessary gain required for neutrino physics applications without the need for the complexities of two-phase operation. One solution would be to use an array of SiPDs as the optical sensors in the liquid. Alternative optical readout options may be possible, such as CCDs, and some may be better suited to reading out the light in the gas phase. Although reverting to two phase operation, such concepts would still have the possible advantage of simplification of the electronics.

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