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Towards improving spatial and energy resolution in gaseous detectors with negative ion drift

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Abstract. Negative ion drift is a technique to minimise diffusion in gaseous detectors by drifting negative ions in lieu of electrons. Electronegative gases are typically used as a method to form negative ions. However, these gases present technical challenges to achieve high gain, preventing widespread adoption. This work leverages an alternative electron attachment approach, Dissociative Electron Attachment, which may produce negative ions in situ from conventional molecular gas species. The method, demonstrated in this work using CF_4, successfully converts the electron signal to negative ions. Our measurements provide new insights into the attachment and detachment processes within gaseous detectors.

1 Introduction

Gaseous detectors are ubiquitous throughout nuclear and particle physics due to their relative simplicity and adaptability to different detection roles. Gas time projection chambers (TPCs) are particularly useful as particle tracking detectors, and may find applications in rare event searches [1–3]. Like all detection systems, gas TPCs have a finite spatial and energy resolution. In many cases, spatial resolution is limited by the pitch of the readout. In contemporary Micro-Patterned Gaseous Detectors (MPGDs), pixel sizes are routinely $O(10\ \mu\text{m})$ [1], allowing superb position resolution along the plane of the readout. The limitation to the spatial resolution in these detectors is often set by the diffusion of primary electrons as they drift in the detector towards the readout plane.

Diffusion in the TPC drift region has previously been minimised via a magnetic field, in large-scale detectors such as those proposed for rare-event detection, this method is not economical and may introduce radioactive backgrounds. An alternative method involves the introduction of an electronegative gas dopant to promote the formation of negative ions close to the primary ionisation track [4]. This process of Negative Ion Drift (NID), could be utilised to improve spatial resolution in MPGDs, since negative ions drift with low diffusion, at the thermal limit [5]. Additionally, since the slow drift velocities in NID can allow individual carriers to be resolved in time, measurements that count the number of ion-induced avalanches can remove gain variations from energy estimates, improving detector energy resolution to the statistical limit [6].

Current NID experiments utilise SF_6 as a detector gas due to it's high electronegativity and beneficial qualities as a target material in rare event searches [7]. In detectors requiring a Townsend avalanche for measurement, detachment of the electron from the negative ion at the amplification stage remains a limiting factor which results in lower operational gains [6]. Furthermore, some electronegative gases present environmental and safety hazards which complicate operational use. A plausible means of overcoming the challenges with existing NID gases is to find a low-hazard NID gas with improved gain characteristics. The approach explored in this work is to use a conventional low-hazard gas known to have excellent gain characteristics, and to form negative ions via *Dissociative Electron Attachment* (DEA). CF_4 is used throughout this work as it is common conventional detector gas known to have no long-lived electronegative component [8, 9]. DEA uses energetic electron-molecule interactions to break molecular bonds and form a negative ion from fragments of the parent molecule. This process therefore requires sufficient electron energy to overcome the energetic DEA threshold and can be achieved by increasing the reduced electric field within the detector. The reduced field required to overcome the DEA threshold from theoretical models is approximately 20 Td [10], which is well above conventional TPC drift fields.

2 Experiment

A series of experiments were conducted to observe the negative ion formation via DEA using a modified version of the CYGNUS-n detector at the Australian National University (see Figure 1). The experimental setup consisted of

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a 3 cm drift region between a stainless steel mesh cathode and a 50 μm thick Gas Electron Multiplier (GEM). To establish the electric fields within the detector, the drift field was maintained by a bias on the cathode with the top of the GEM grounded. The amplification stage at the GEM was achieved by applying a positive voltage to the bottom of the GEM.

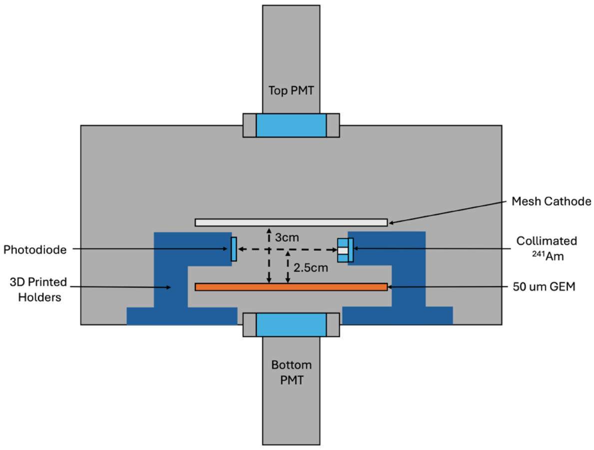

Figure 1: Labeled diagram of the CYGNUS-n experimental setup used for DEA studies.

The detector was enclosed within a pressure vessel which contained the CF_4. To prevent the possible effects from contamination and out-gassing, the detector was pumped to pressures below $1{\times}10^{-3}$ Torr overnight prior to operation. The detector operated below atmospheric pressure and with a constant flow of gas supplied by a mass flow controller to mitigate the impact of breakdown products, with the pressure kept constant using a vacuum controller. Detector operating pressures for this experiment ranged between 15 and 50 Torr.

Ionisation tracks from alpha particles were introduced using an ^{241}Am source which was collimated parallel to the GEM plane. The alpha particles were detected by a silicon photodiode placed on the opposite side of the TPC drift region, which served as the trigger for the data acquisition system. Primary and secondary scintillation light caused by the initial ionisation track and avalanche respectively were observed by two 1.5 inch Photomultiplier Tubes (PMTs) through windowed flanges. The PMTs were located above and below the drift volume, external to the vacuum vessel. Data was recorded on a CAEN 2740 digitiser. For each experimental pressure, the reduced field in the drift region was set by applying a bias to the cathode over the range of the high voltage supply, up to its maximum magnitude of -6 kV. At each reduced field at least 5000 alpha particle events were recorded for analysis.

3 Results

Digitised PMT waveforms above and below the DEA threshold are presented in Figure 2. At high drift fields, a large number of delayed scintillation events occur, and no such delayed events occur at low fields out to 1 ms. We attribute these delayed photon signals to avalanche scintillation from negative ions – either F^- or CF_3^- – generated via DEA.

A measure of ‘integrated signal intensity’ was used to quantify the amount of light observed in a given region of the waveform below a baseline threshold. Two time windows were selected. The first spanned between sample 150 and 400 (1.2-3.2 μs) and encompassed both the primary and avalanche light caused by electron drift. The second, delayed window began after 400 samples (3.2 μs), where low drift fields saw no subsequent signal, and extended to the end of the waveform, so corresponds to the ion signal. A plot of integrated signal intensity for electrons and negative ions as a function of reduced field for a pressure of 25 Torr is presented in Figure 3. At each observed pressure, the delayed negative ion signal is absent until after the expected 20 Td DEA threshold is surpassed. Measurements beyond this threshold show an increase in the ion signal and a corresponding decrease in the electron signal. In pressures below 35 Torr, the electron signal is completely converted to an ion signal within the drift volume of the detector. Our results also suggest a high negative ion gain, much more comparable to the electron gain than is typical of SF_6. The best observed signal recovery was found at 30 Torr, where the negative ion signal reached 80 % of the maximum electron signal.

The optical measurements of negative ion arrivals with a fast PMT meant negative ion avalanches were separable in time, allowing single ion counting techniques to be explored in future studies. The observation of single ions also allows the single carrier gain curve to be elucidated, which may shed light on negative ion detachment processes in the avalanche [6], which is not well understood [11].

4 Conclusion

Detectors utilising negative ion drift present opportunities for improving detector resolution in future experiments. Previous efforts have focused on introducing electronegative gas dopants, which present technical challenges. This work introduces a method to produce and drift negative ions within the detector without an electronegative gas species via dissociative electron attachment. We have demonstrated the production of negative ions via this method using CF_4, at pressures between 15 and 50 Torr, with excellent ion avalanche gain compared to electrons.

As the demonstrated technique observes individual ions at the readout stage, this presents further opportunities to study fundamental electron-molecule interactions within a detector environment.

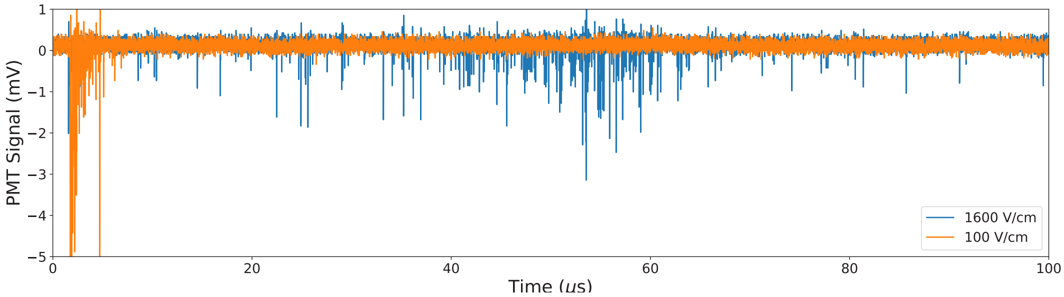

Figure 2: Baseline-subtracted signals from the bottom PMT. Both signals are recorded in 20 Torr pure CF_4 with (Orange) 100 V/cm drift field (Blue) 1600 V/cm drift field.

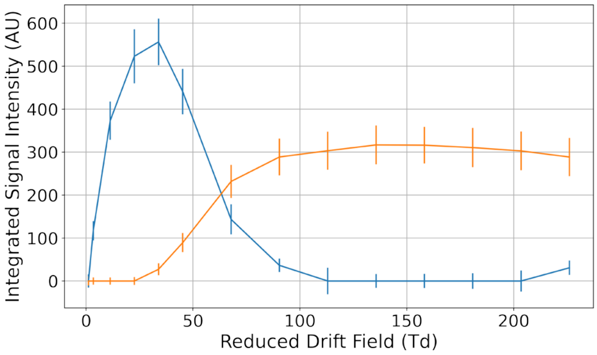

Figure 3: Integrated signal intensities of electron (Orange) and ion (Blue) signals for a detector containing 25 Torr CF_4.

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