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Study and mitigation of spurious electron emission from cathodic wires in noble liquid time projection chambers

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ABSTRACT

Noble liquid radiation detectors have long been afflicted by spurious electron emission from their cathodic electrodes. This phenomenon must be understood and mitigated in the next generation of liquid xenon (LXe) experiments searching for WIMP dark matter or neutrinoless double beta decay, and in the large liquid argon (LAr) detectors for the long-baseline neutrino programmes. We present a systematic study of this spurious emission involving a series of slow voltage-ramping tests on fine metal wires immersed in a two-phase xenon time projection chamber with single electron sensitivity. Emission currents as low as 10^{-18} A can thus be detected by electron counting, a vast improvement over previous dedicated measurements. Emission episodes were recorded at surface fields as low as $\sim$10 kV/cm in some wires and observed to have complex emission patterns, with average rates of 10–200 counts per second (c/s) and outbreaks as high as $\sim 10^6$ c/s. A fainter, less variable type of emission was also present in all untreated samples. There is evidence of a partial conditioning effect, with subsequent tests yielding on average fewer emitters occurring at different fields for the same wire. We find no evidence for an intrinsic threshold particular to the metal-LXe interface which might have limited previous experiments up to fields of at least 160 kV/cm. The general phenomenology is not consistent with enhanced field emission from microscopic filaments, but it appears instead to be related to the quality of the wire surface in terms of corrosion and the nature of its oxide layer. This study concludes that some surface treatments, in particular nitric acid cleaning applied to stainless steel wires, can bring about at least order-of-magnitude improvements in overall electron emission rates, and this should help the next generation of detectors achieve the required electrostatic performance.

1. Introduction

Two-phase xenon detectors employed in direct dark matter searches, such as that being developed for the LUX-ZEPLIN (LZ) experiment [1] which motivated this study, require extremely low thresholds for scintillation and ionisation signals, at the level of single quanta [2,3]. Although this technology has been at the forefront of the field for several years, it remains the case that most such LXe Time Projection Chambers (LXe-TPCs) have not been able to operate at their design electric fields. Similar problems have afflicted this technology applied to neutrinoless double beta decay searches, as well as LAr instruments for both dark matter and neutrino detection. Although these difficulties have long been recognised, a definitive explanation is still lacking. A review of the various high-voltage (HV) issues affecting these communities can be found in Ref. [4].

Aside from any difficulties related to the HV feedthrough technology, where progress has been made in recent years, the prominent limitation which has often materialised can be traced to the poorly understood emission of light and charge specifically from the wire grids used to define the various field regions. In two-phase detectors these include the cathode wire-grid at the bottom of the sensitive volume and the gate wire-grid located just below the liquid surface, which are both cathodic electrodes. They define a ‘drift field’ between them which sweeps the ionisation released by particle interactions in the active liquid volume; the gate also strengthens the ‘extraction field’ below the liquid surface, promoting electron emission and the subsequent generation of the electroluminescence response in the vapour phase. These grids are typically made from parallel or woven metal wires with diameters of tens to hundreds of micrometers. Spurious emissions are observed at electric fields as low as 10 kV/cm on the wire surface,[1] much

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[1] Surface fields are calculated for the perfect (cylindrical) wire geometry unless indicated otherwise.

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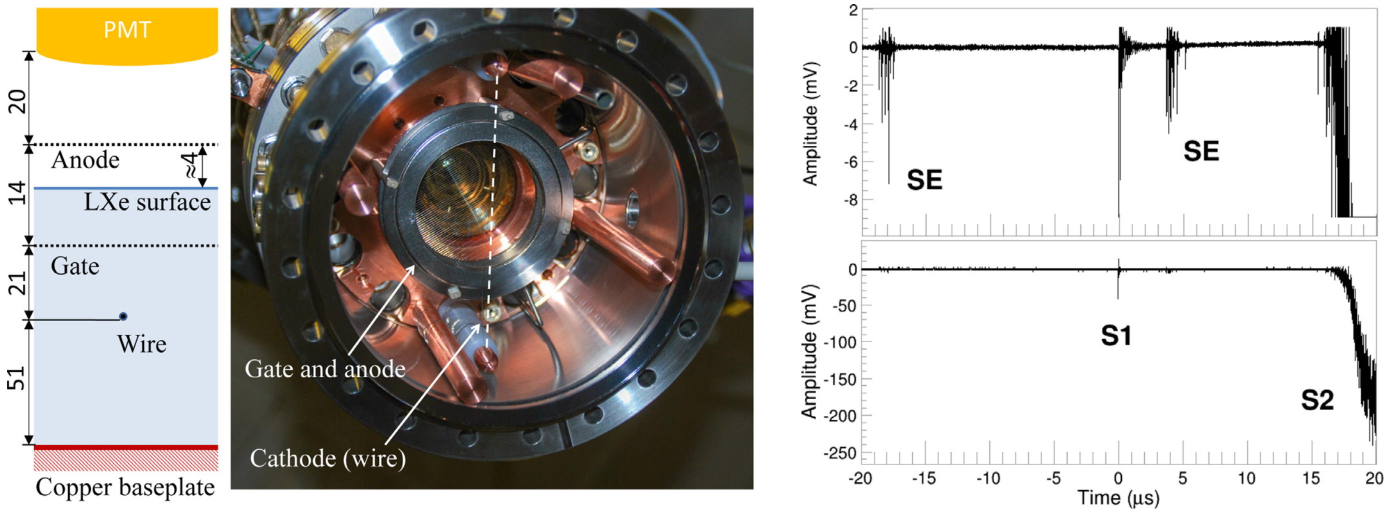

Fig. 1. Left – Schematic of the chamber (dimensions in mm). Centre – Upward view of the chamber with the copper baseplate removed. The PMT is visible through the 60 mm wide gate and anode grids which establish electroluminescence above the liquid surface. The cathode wire sample (highlighted) is stretched between the two feedthroughs as shown. Right – Typical waveform recorded with a 100-μm ZEPLIN-III wire with 145 kV/cm on its surface, in the high- and low-gain channels. The ringing visible in the waveform is due to the use of an external PMT voltage divider. A large S2-like signal (seen clearly in the lower, low-gain channel) is preceded by an S1-like optical pulse followed by a SE pulse, attributed to photoionisation by the S1 light. Another SE is registered prior to S1, which constitutes a candidate pulse from spurious emission.

lower than expected for phenomena such as liquid-phase electroluminescence and field emission; these have prevented the operation of previous instruments at their design voltages: the threshold of these dark matter detectors is so low (especially in the ionisation channel) that the emission of individual electrons and photons can interfere with the physics searches, which aim to detect ∼keV energy deposits containing very few scintillation photons and ionisation electrons. Spurious emissions from electrode grids also jeopardise the so-called ‘S2-only’ searches (using electron counting below the scintillation threshold) [5–7], as in this type of analysis the accurate reconstruction of the vertical coordinate is not possible.

Although detection thresholds for ionisation are typically much higher in the large LAr-TPCs for neutrino detection, electrons emitted by any cathodic surface may be drifted long distances and accumulate on dielectric surfaces several metres away and lead to discharges later on. In this instance it is not trivial to diagnose that this process may be taking place at all.

The electrostatic design methodology adopted by previous experiments was thus found to be compromised. This was based on the onsets for electroluminescence and charge multiplication in LXe at 412^{+10}_{-133} kV/cm and 725^{+48}_{-139} kV/cm, respectively [8] (see also [9,10]), while practical LXe-TPC cathodes made from stainless steel wires have been limited to surface fields of 40–65 kV/cm [11–16]. A detector with gold-plated stainless steel wires could not operate at the design field either [17]. A chamber with Monel wires, known for its resistance to corrosion, sustained 35 kV/cm on the gate grid [18]. Notably, a small chamber achieved substantially higher fields of 220 kV/cm on BeCu wires [19]. Spurious emission has been reported also in detectors using etched meshes instead of wires (e.g. [20]).

This study set out to determine the underlying causes for this phenomenology and to attempt to find suitable mitigation by testing systematically a number of fine cathodic wires a few centimetres long for the emission of quanta of light and/or charge in a small two-phase xenon chamber built for this purpose. This work was conducted within the wider R&D framework for the LZ experiment, in particular in coordination with colleagues at SLAC where larger electrodes are being tested; these involve ∼10 m of wire initially, followed by validation of the full LZ grids utilising $\gtrsim$700 m of wire (see Section 3.10 in [1] for additional information on this programme).

2. Experimental Method

2.1. Two-phase xenon chamber

The small (4 kg) LXe chamber depicted in Fig. 1 was developed for these tests. Gate and anode wire-grid electrodes are located just below and above the liquid surface, respectively; these grids were built from 100 μm wire (SS316L) with 1 mm pitch, oriented at 90° to each other. The cathode wire-grid which would normally exist at the bottom of the active volume was replaced by a single thin wire (the sample under study), located 21 mm below the gate. Thus a strong electric field is achieved at the wire surface with only modest voltages delivered into the chamber. In the basic test, the field on the wire surface is increased steadily, and single electron (SE)-like signals which are unrelated to any particle interaction in the chamber are searched for in the subsequent data analysis. Particle interactions (which are not the focus of this study) are detected via prompt scintillation (S1) and delayed electroluminescence (S2) signatures; an example is shown in Fig. 1 (right), along with two SE pulses.

At the bottom of the chamber, a thick copper baseplate is cooled to ≈−100 °C by a long ‘cold finger’ immersed into an open LN_2 dewar located under the detector, providing 12 W of cooling power. Thermal control is achieved through external heaters attached to the baseplate. Despite that, this is the coldest detector surface, providing a good thermal profile to avoid bubbling.

A 2-inch, quartz-windowed ETEL D730/9829Q photomultiplier tube (PMT) is located in the gas phase viewing downward. Electrons released from the upper surface of the test wire are drifted upward past the gate and emitted into the vapour phase, where they generate electroluminescence. This provides sensitivity to single electrons emitted from the wire, which was the key design driver. Although the wire length is 130 mm, the length effectively under test is just over 50 mm (cf. Section 2.4).

The wire sample is cleaned prior to installation in two consecutive, 1 h long ultrasonic baths in scientific grade acetone and isopropyl alcohol, then dried with a jet of filtered argon gas. After assembly of the sample, which requires the chamber to be exposed to air for about one hour, the system is warmed to 50 °C and pumped to high vacuum for 2–4 days while monitoring the pressures of electronegative species. Xenon gas is then introduced and