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Secondary scintillation yield from gaseous micropattern electron multipliers in direct Dark Matter detection

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ABSTRACT

Efforts are being made in direct Dark Matter search experiments to detect the primary ionisation in the liquid by extracting the electrons to the gas phase and use the secondary ionization produced in the micropattern electron multipliers for signal amplification in noble-liquid dual-phase TPCs. We have studied the secondary scintillation yield of a single Gas Electron Multiplier (GEM) and of a Micro-Hole & Strip Plate (MHSP) for xenon at room temperature. Values for secondary scintillation yield between 5.0×10^3 and 1.3×10^3 photons per primary electron were obtained for the GEM and between 7.2×10^4 and 1.8×10^3 photons per primary electron for the MHSP, as the pressure increased from 1.0 to 2.5 bar in the GEM-setup and from 1.0 to 3.3 bar in the MHSP-setup, respectively. These values can be more than one order of magnitude higher than what has been obtained in the uniform-field scintillation gaps of the XENON and ZEPLIN-III experiments. Although in the present setups the amount of secondary scintillation obtained is sufficient in view of the use of PMTs, if a different type of readout is considered, such as large area avalanche photodiodes, it will be important to increase the amount of secondary scintillation. The attained results demonstrate the clear advantage of reading the secondary scintillation instead of the charge produced in the electron avalanches of micropattern electron multipliers, in low-background and low-rate experiments, as is the case in direct Dark Matter search.

1. Introduction

The search for "cold" Dark Matter predicted by the Standard Model is a major motivation for important experiments in contemporary particle physics and cosmology. The Weakly Interacting Massive Particles (WIMPs) may produce nuclear recoils with energies ranging from a few to 100 keV. The simultaneous detection of both ionisation and scintillation signals in a noble-liquid can lead to a unique signature for the energy deposited by a recoiling nucleus in the target volume, like the ICARUS Collaboration already showed in 1993 [1]. Cryogenic, dual-phase optical TPCs have been recently developed for Dark Matter search, in experiments such as XENON, ZEPLIN, LUX and WARP, e.g. [2–4]. The primary ionisation resulting from radiation interaction in the liquid is extracted to the gas phase and amplified through secondary scintillation production in a uniform-field scintillation gap, being the scintillation recorded by photomultiplier tubes (PMTs).

Alternatives to secondary scintillation production and readout, as amplification process for primary ionisation, are under investigation and/or implementation for large scale detectors, making use of the secondary avalanche ionisation produced in micropatterned electron multipliers, such as Gas Electron Multipliers (GEMs), Thick-GEMs (THGEMs), MICROMEGAS and Large Electron Multipliers (LEMs) [5–9]. LEMs are to be used in ArDM [10] and in the recently proposed GLACIER [11] programmes. GEMs and THGEMs are under investigation for ZEPLIN and LUX, respectively [5–7]. The simplicity, low cost and much less mass burden of the charge readout system would be an important advantage over the scintillation readout with PMTs.

However, the limited signal amplification achieved in charge readout mode presents a serious drawback in these attempts. Given the characteristic low rate and high radiation background of these experiments, to effectively discriminate nucleus-recoiling events from the background it is crucial to have the highest possible gain in the detector. Therefore, it is of great importance to use

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the secondary scintillation signal rather than the secondary charge signal. In addition, in opposition to the conventional electronic readout of secondary avalanche charge, the optical recording of the secondary scintillation results in fast propagating pulses that are insensitive to electronic noise, RF pick-up and high-voltage issues, since the readout is physically and electrically decoupled from the gas-multiplication elements.

Hence, it is important to investigate not only the charge but, also, the scintillation capabilities of modern micro-patterned electron multipliers, to demonstrate their capacity of rendering much higher amplification gains with much less statistical fluctuations, when compared to the charge avalanche [12,13]. In addition, for large scale detectors, the secondary scintillation produced in those micropattern electron multipliers presents an alternative to the secondary scintillation produced in uniform field scintillation gaps, commonly used in this type of instrumentation. It is possible to reach larger scintillation outputs for much lower applied voltages at the cost of a small degradation in the statistical fluctuations of secondary scintillation. The increase in the secondary scintillation output is important if other type of readout, such as large area avalanche photodiodes (LAAPD), is used substituting for PMTs.

In this work, we have studied the electroluminescence yield of GEMs in pure xenon, in the pressure range of 1–2.5 bar. A VUV-sensitive LAAPD was used for secondary scintillation readout. The GEM electroluminescence yield as well as the amplitude and energy resolution of the scintillation pulse-height distributions were determined as a function of GEM voltage and compared to those of charge pulses. The studies have been performed in pulse-mode, using 22.1 keV X-rays from a ^{109}Cd radioactive source. The electroluminescence yield of a Micro-Hole & Strip Plate (MHSP) operated in xenon at pressures raging from 1 to 3 bar was also studied as a function of MHSP voltage. In this case, a reflective CsI photocathode was used for the scintillation readout and the studies were performed in current-mode.

2. GEM electroluminescence studies

2.1. Experimental set-up and methodology

In Fig. 1 we depict schematically the GEM and the scintillation-readout LAAPD elements. The drift and induction gaps were 8 and 3 mm thick, respectively. The 1-mm diameter collimated 22.1 keV X-ray beam interacting in the drift region induces primary electron clouds that are focused into the GEM holes where they undergo charge avalanche multiplication. A reversed electric field is applied across the induction region to allow full collection of the avalanche electrons on the bottom electrode (anode) of the GEM. A large number of VUV scintillation photons ($\lambda_{peak} \sim 172$ nm) are produced in the charge avalanche as a result of the gas de-excitation processes. A fraction of these photons reaches the LAAPD active-area and the corresponding electric signal is amplified in the photodiode [14].

The secondary, or proportional, scintillation is also called electroluminescence which yield, Y, we define as the number of secondary scintillation photons produced per drifting primary electron. For pressures above a few tenths of bar the electroluminescence spectrum of xenon consists of a narrow line peaking at 172 nm, with 5 nm FWHM [15], called the second continuum. It corresponds to transitions of the singlet and triplet bound molecular states, from vibrationally relaxed levels, to the repulsive ground state. At atmospheric pressure, most of the emission is centered in the second continuum, being the emissions in the visible and in the IR regions negligible in comparison with those in the VUV range [15,16].

The processes leading to emission in the second continuum occur through three-body collisions and can be schematized by

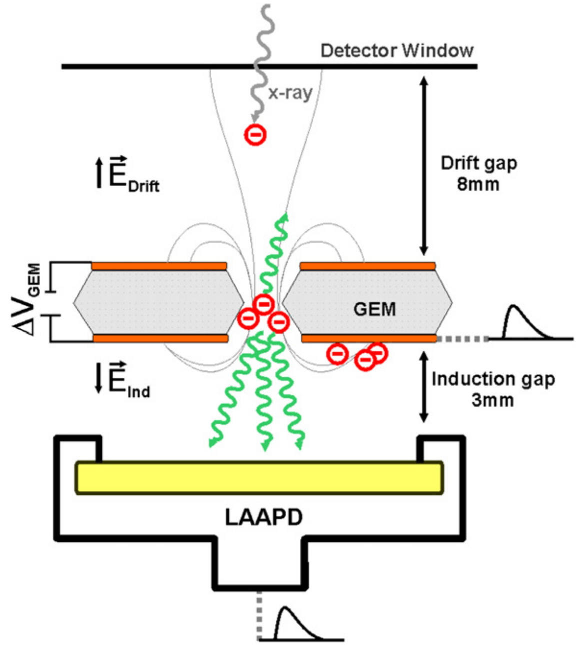

Fig. 1. Schematic diagram of the single-GEM instrumented with a LAAPD for the electroluminescence readout. The charge signals are recorded at the GEM's anode.

$$Xe^* + 2Xe \rightarrow Xe_2^* + Xe,$$

$$Xe_2^* \rightarrow 2Xe + h\upsilon.$$

One excited atom creates an excited excimer, Xe_2^*, which decays emitting one VUV photon, $h\upsilon$.

Concurrent with the electroluminescence due to the absorption of X-rays in xenon, a large fraction of the X-rays is detected directly by the LAAPD. For a given X-ray energy, the amplitude of the signals due to X-ray interaction in the photodiode depends only on the LAAPD bias, regardless of the GEM voltage. The number of electron–hole pairs, $N_{e,XR}$, produced by direct absorption of the X-ray in the LAAPD is determined from the energy of the X-ray and the w-value in silicon ($w = 3.62$ eV) and is approximately 6.1×10^3 electron–hole pairs for $E_x = 22.104$ keV.

A direct comparison between the amplitudes of the GEM electroluminescence, A_{Sc}, and the directly absorbed X-rays, A_X, provides a quantification of the number of VUV-photons, N_{UV}, impinging the LAAPD per X-ray absorbed in the xenon drift gap,

$$N_{UV} = \frac{A_{Sc}}{A_X} \times \frac{N_{e,XR}}{QE}, \tag{1}$$

where QE is the quantum efficiency of the device, defined as the number of charge carriers produced per incident VUV photon, being 1.1 for 172-nm photons [14,17].

The GEMs used in this work were manufactured at CERN and had standard dimensions, i.e. a 50-μm Kapton foil with a 5-μm copper clad on both sides and bi-conical holes of 50 and 70 μm diameter in the Kapton and copper, respectively, arranged in a hexagonal layout of 140-μm edges. The GEM's active area was 2.8×2.8 cm^2.

A stainless-steel chamber was built to accommodate both GEM and LAAPD and was filled with pure xenon at different pressures, being sealed off during the measurements. The maximum pressure at which the LAAPD can operate safely is 2.5 bar. The gas purity was maintained by convection through non-evaporable getters (SAES St707), heated up to about 140 °C. The LAAPD enclosure and the chamber were grounded, while the radiation window and the GEM's top and bottom electrodes were biased independently. Constant drift- and induction-fields of 0.25 and −0.1 kV/cm, re-