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Development of gas avalanche photodetector operating at cryogenic temperature

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Abstract

We are interested in developing a photodetector sensitive to liquid noble gas scintillation light which is able to operate in cryogenic environment down to liquid nitrogen temperature (77 K). It has to be a simple, cheap and compact device, with a photocathode surface comparable to that of photomultipliers, and it has to be able to produce fast signals for timing and triggering purposes. It could offer a cheap alternative to the photomultiplier use in large volume time projection chambers operating in liquid noble gas.

We studied the possibility to couple a standard photocathode to a suitable electron multiplication system in gas. The results of the evaluation of the maximum gain attainable in gas employing pure argon and argon/methane mixture at low temperature are presented.

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Keywords: Photodetectors; Gas avalanche multiplication; Cryogenic detectors; Liquid argon TPC

1. Introduction

Scintillation light produced in liquid argon (LAr) (128 nm wavelength) is detected in some experimental set-ups dedicated to neutrino physics, proton decay and dark matter searches, using photomultiplier tubes (PMTs) immersed in the liquid phase [1] or placed in gas phase above the liquid [2].

In the cases in which big liquid masses are involved and the light signal is used only for timing and triggering purposes, it could be interesting to develop cheap photodetectors operating in cryogenic environment as an alternative solution to the PMT use. This device has to be simple, compact and characterized by large sensitive area. Gains of the order of 10^3–10^4 could be sufficient for the mentioned purposes.

The possible employment of gas avalanche multiplication of photoelectrons was studied. Photoelectrons were produced in a standard photocathode by ultraviolet photons in order to evaluate the maximum attainable gain at LAr temperature (87 K). For practical reasons the cryogenic tests were carried out at liquid nitrogen temperature (77 K), which is close to that of LAr.

Since we would operate with a gaseous detector immersed in the liquid phase it is necessary to choose an appropriate gas mixture and pressure in order to prevent condensation. In the first phase of the programme we used pure argon (99.999% purity, vapour pressure at liquid nitrogen temperature ~200 mbar corresponding to an atomic density of $4.90 \times 10^{18}\,\mathrm{cm}^{-3}$ at 300 K). Then we repeated the measurements adding a quencher. Argon/methane mixture (argon 95 vol%; methane 5 vol%) was employed maintaining methane partial pressure below its vapour pressure at liquid nitrogen temperature (~10 mbar).

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2. Experimental set-up

The detector layout is shown in Fig. 1. The device is made up of:

- the photocathode K, consisting of a stainless steel plate (3 mm thick, 35 mm diameter) in which a gold plated copper disk is encapsulated (1 mm thick, 18 mm diameter);
- two nickel mesh grids GK and GA fixed on a ring (35 mm external diameter, 24 mm internal diameter), used to segment the chamber volume in three different zones (generation, drift and multiplication);
- three field-shaping stainless steel rings RT1, RT2 and RT3 (35 mm external diameter, 24 mm internal diameter), used to keep the electric field uniform in the drift zone;
- the electrode A, used to bound the multiplication zone;
- the collection grid G (35 mm diameter), used for electron multiplication and charge collection. It was made fixing a stainless steel wire (AISI 304L, 50 μm radius) on a PEEK^{TM} support (2 mm wire spacing) while tensioning it at 500g [3].

Bunches of electrons are extracted from the photocathode K via photoelectric effect (gold photoelectric threshold $E_{th}\sim4.9$ eV) by means of UV photons provided by a pulsed xenon lamp (repetition rate $\sim$1 Hz) and brought to the photocathode by means of an optical fibre. The electron bunch moves towards the anode along the electric field lines crossing the drift region and approaching the collection grid wires, where the charge is multiplied. The device operates as a multiwire proportional chamber (MWPC) in which all the sensitive wires are connected together.

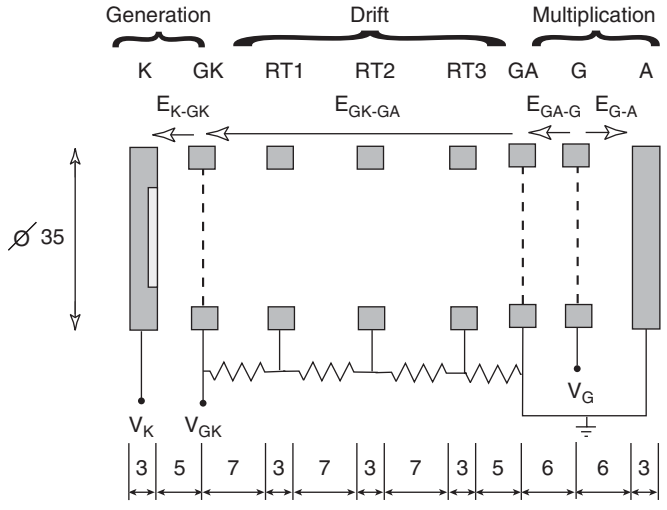

Fig. 1. Schematic view of the detector. Numbers represent the dimensions in mm. Electrical scheme of the connections and electric field directions are also shown.

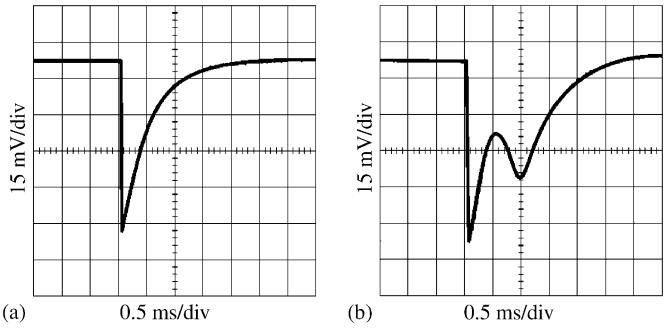

Fig. 2. (a) Photocathode signal waveform when the device operates as an ionization chamber ($p_{Ar} = 10$ mbar; $T\sim300$ K). (b) Photocathode signal waveform at the same pressure and temperature conditions, when the device operates as a proportional chamber.

The electrode voltages are chosen in order to guarantee the transparency of the grids to the crossing electrons, according to the rule of Ref. [4]. The chosen drift fields (Fig. 1) are $E_{K-GK} = 20$ V/cm and $E_{GK-GA} = 50$ V/cm while the mean field $\langle E_{GA-G}\rangle$, equal to $\langle E_{G-A}\rangle$, in the multiplication region ranges from 100 V/cm to 2 kV/cm.

3. Study of Ar^+ ion feedback

The typical waveform of a photocathode signal is shown in Fig. 2(a); it was recorded in pure gas argon ($p_{Ar} = 10$ mbar; $T\sim300$ K) with a multiplication factor equal to 1, in order to avoid e^-/Ar^+ pairs production; in this condition the device operates as an ionization chamber. When the collection grid voltage exceeds the ionization threshold voltage, the multiplication process takes place with e^-/Ar^+ pair production in proximity of the collection grid wires; the device operates as a proportional chamber. The electrons quickly reach the grid where they are collected; the ions drift towards the cathode with a velocity about one thousandth of the electron one. The choice of the electric field behind and in front of the grids GA and GK makes them almost opaque to the ions, but about 0.4% of the produced ions (for $\langle E_{GA-G}\rangle = 600$ V/cm) overcome them reaching the photocathode and producing the second peak in the cathode signal waveform (Fig. 2(b)). As Ar^+ ions lose part of their initial energy crossing the GK–GA region, when they hit the photocathode their kinetic energy is not sufficient to extract new photoelectrons, thus avoiding a cascade process. The delay of the second peak is proportional to the Ar^+ drift velocity. Decreasing the drift field E_{GK-GA}, a progressive increase of the delay is observed. The ion mobility of gas argon measured is $1.35 \pm 0.05\,cm^2\,V^{-1}\,s^{-1}$ (reduced to pressure and temperature normal conditions).

4. Gain curves of gaseous detector immersed in LN_2

Gas multiplication factor (gain) is evaluated from the ratio between the signal amplitude S_G (proportional to the