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Further studies of two-phase krypton detectors based on gas electron multipliers

A. Bondar, A. Buzulutskov [*], D. Pavlyuchenko, R. Snopkov, Y. Tikhonov

Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia

Abstract

We further study the performances of cryogenic two-phase (liquid-gas) detectors, based on Gas Electron Multipliers (GEMs) and operated in an avalanche mode in Kr. Stable operation of the triple-GEM multiplier in saturated vapor, above the liquid, has been demonstrated for a few hours. Charging-up effects were observed in GEM-based two-phase detectors at high anode currents. In a pulse-counting mode, the maximum gain of the triple-GEM in two-phase Kr could not exceed 1000. The signals induced by 0.5 MeV γ-rays were recorded from the two-phase detector in coincidences with a BGO counter, aiming at potential applications in Positron Emission Tomography.

Keywords: Gas Electron Multipliers; cryogenic avalanche detectors; two-phase detectors; noble gases.
PACs: 29.40.Cs; 34.80.My.

1. Introduction

In recent years, there has been a growing interest in the development of cryogenic two-phase detectors based on noble liquids for “low energy” physics experiments, where the deposited energy is rather low: of the order of 1 keV in coherent neutrino scattering [1], 10 keV in dark matter search [2], 100 keV in solar neutrino detection [3] and 1 MeV in Positron Emission Tomography (PET) [4]. The liquids proposed for using in these experiments are argon, xenon, helium and xenon respectively. The primary ionization signal in such experiments is rather weak; therefore it should be amplified. The development of cryogenic avalanche detectors [5] might solve the problem: such detectors should be able to operate in an electron-avalanching mode in saturated vapor of the noble gas, above the liquid phase.

At present, the operation in pure noble gases at reasonable gains is possible using either Gas Electron Multipliers (GEMs) [6] or Micro-Strip Hole Plates (MHSP) [7], the latter structure being actually a modification of the GEM. High gain operation of GEM structures was demonstrated in all noble gases at room temperature [8-10] and in He, Ar and Kr at cryogenic temperatures [5,11,12]. First results from the GEM operation at cryogenic

[*] Corresponding author. Email: buzulu@inp.nsk.su

temperatures in two-phase Kr detectors have been recently presented in our works [5,11]: gains exceeding 1000 and stable operation for one hour were reported.

It should be remarked however that the stability of electron avalanching in saturated vapor is still under question. In the past this was the main obstacle preventing the development of two-phase detectors [13]: gain instabilities were observed in two-phase Kr and Xe detectors based on wire chambers. These instabilities were believed to arise due to vapor condensation on wire electrodes, enhanced by the electric field.

Therefore further studies of GEM performances in two-phase detectors are of primary importance. It should be noted that the GEM operation in Kr is very similar to that in Xe and in less extent in Ar [8,9]. So that the basic characteristics of two-phase avalanche detectors in heavy noble gases might be obtained studying their performances in Kr.

In the present paper we further study two-phase Kr avalanche detectors based on GEM structures. The stability of operation, charging-up effects and detector response to γ-rays, aiming at their potential applications in PET, are studied.

2. Experimental setup

Most results presented in the following sections are obtained using an improved modification of the experimental setup described in Refs. [11,12]: see Fig.1. The setup consists of a vacuum-insulated chamber, of a volume of 2 l, equipped with three GEM foils mounted in cascade inside. The chamber is cooled from the top using a heat exchanger mounted on the flange. At all times the chamber is connected to the bottle with a certain amount of Kr: in the two-phase mode it provides a liquid Kr layer of a volume of 50 ml and thickness of 2-3 mm.

The improvements of the setup are as follows. It was better stabilized in the two-phase mode, adjusting the liquid nitrogen flow through the heat exchanger using a cold valve. The krypton purity was increased: the gas was passed through an Oxisorb filter each time the setup was cooled down and warmed up. To suppress the waves on the liquid surface, a copper screen was installed inside the chamber to protect against droplets falling from the heat exchanger: just these droplets provide the heat transfer between the top and the bottom of the chamber. In addition, the liquid layer thickness was monitored measuring the capacitance of the cathode gap, i.e. between the cathode and the first GEM.

GEM electrodes were biased through a resistive high-voltage divider placed outside the cryostat. The divider was similar to that used in Refs. [11,12], with three identical circuits connected in parallel [11,12]. The divider was at the positive potential, the cathode at the negative potential and the 1st electrode of the first GEM was grounded.

The detector was irradiated with X-rays from an X-ray tube, β-particles from a ^{90}Sr source or 0.51 MeV γ-rays from a positron ^{22}Na source. In the latter case, a scintillation BGO counter was used to provide coincidences between two γ-quanta.

Other details of the experimental setup and procedures are described elsewhere [11,12].

3. Operation in the two-phase mode

In the two-phase mode, there is a strong correlation between the temperature and the vapor pressure. Therefore monitoring the pressure provides a precise estimation of the temperature. To monitor the presence of the liquid layer at the bottom of the chamber, the capacitance of the cathode gap, between the cathode and GEM1, was measured: it should be a linear function of the layer thickness. Fig. 2 shows this capacitance as a function of the gas pressure during cooling and heating procedures. The capacitance enhancement, by about 0.2 pF in the pressure range of 0.9-1.3 atm, indicates the presence of the liquid layer.

It is interesting that at a pressure below 0.9 atm, near the pressure corresponding to that of the triple point of Kr, the capacitance returns to the initial value, indicating disappearance of the liquid layer. This takes place because the krypton becomes solid if overcooled, resulting in that the transfer of the heat and the liquid from the heat exchanger is suppressed. In these conditions, all krypton would finally condense at the coldest part of the chamber, i.e. in the vicinity of the heat exchanger.

The threshold behavior of electron emission from the liquid into the gas, as a function of the electric field, is the characteristic property of two-phase systems: for Kr it has been demonstrated in Ref. [5,11] in the current (ionization) mode of operation. Fig. 3 demonstrates this property in the pulse-counting (amplification) mode, at a triple-GEM gain of about 250: the anode pulse-height is shown as function of the electric field in liquid Kr. The latter was calculated using the formula obtained with an account of boundary conditions for the electric field at the liquid-gas interface:

$$E_L = V/(d_L + d_G \varepsilon_L / \varepsilon_G)\,.$$

Here V is the voltage applied to the cathode gap, d_L and d_G the liquid and gas layer thickness, ε_L and ε_G the dielectric constant of the liquid and the gas.

We observed the charging-up effect in two-phase Kr at high anode currents: Fig. 4 shows a comparison of gain-voltage characteristics in the current and pulse-counting mode. In the current mode, the gain increase with voltage is faster than exponential at gains exceeding 200, due to charging-up effect. At these gains the anode current density was of the order of 10 pA/mm^2. In the pulse counting mode, where the current density was lower by several orders of magnitude, no charging-up effects were observed. In addition, no charging-up effects were observed in the gaseous mode in Kr, at gains and anode current densities exceeding 10^4 and 1 nA/mm^2 respectively [11]. This means that the charging-up effect was induced by exactly the presence of two phases.

The charging-up effect might be due to ion backflow from the avalanche region which may result in ion accumulation at either the liquid-gas interface or the GEM electrodes. In the latter case, the liquid insulation film, which might be formed on the GEM electrodes due to condensation of saturated vapor, could prevent neutralization of the ion charge. Accordingly, the ion charge would enhance the electron emission from the surface, resulting in increase of the gain due to secondary signals.

This could also prevent operation at high gains and voltages in a pulse-counting mode. Indeed, it turned out that the maximum gain in two-phase Kr in the pulse-counting mode did not exceed 1000 due to the discharge onset (Fig.4). Note that this limit is by an order of magnitude lower than that observed in gaseous Kr [11].

The operation stability of the triple-GEM multiplier in two-phase Kr was studied at a moderate gain, of about 120. Fig. 5 shows the time evolution of the average anode pulse-height and capacitance of the cathode gap, in a pulse-counting mode. The pulse-height was relatively stable for almost 3 hours. Its fluctuations during this period, of about 10-20 %, were not correlated to the liquid layer thickness: they were in fact induced by the pressure variations. At the end of the run, the disappearance and reappearance of the signal was distinctly correlated to the drop and recovery of the gap capacitance. This event was also correlated to the pressure drop. These correlations indicate that the overcooling took place here, followed by disappearance of the liquid layer similarly to that observed near the triple point in Fig.2.

4. Results with γ-rays

^{22}Na source is a positron source producing a pair of collinear γ-quanta via positron annihilation. In PET devices the coincidences between two γ-quanta provide the trigger for image reconstruction. We tried to detect such coincidences using a GEM-based two-phase detector and a scintillation BGO counter (Fig. 1).

Fig. 6 shows the anode signals from the triple-GEM, a signal from the BGO counter and the time delay spectrum of BGO signals with respect to GEM signals. Despite the fact that the liquid Kr layer was too thin for efficient detection of γ-rays, the coincidences between the two-phase detector and the BGO counter were successfully recorded, at a rather low background of random coincidences (see the time delay spectrum). The events were triggered by the GEM signals using signal-above-threshold technique.

Time delay spectra of BGO signals with respect to GEM signals are shown in Fig. 7, at different cathode voltages. The latter defines the electric field in the cathode gap. One can see that the delay and the width of the spectra decrease with the electric field. We will see that this is related to the increase of the electron drift velocity in liquid Kr.

Since the primary ionization electrons are practically uniformly distributed across the liquid layer, the width of the delay spectrum is mainly determined by the layer thickness and the electron drift velocity in the liquid. One can try to estimate the liquid layer thickness analyzing the left edge of the spectrum: its shape is defined mainly by the layer thickness, in contrast to the right edge, since the rise time of BGO signals is rather small (see Fig.6). Correspondingly, the GEM-BGO signal time spread (FWHM), Δt, was estimated fitting the left edge of the spectra (see Fig. 8): it varied between 0.5 and 0.7 μs. Thus, the lower estimate of the liquid layer thickness would be the quantity $v\Delta t$, where v is the electron drift velocity in liquid Kr [14]. Fig. 8 shows this estimation as a function of the electric field: its value, between 2 and 2.5 mm, corresponds to expectations and is in agreement with calculations accounting for the amount of Kr available in the system (see section 2).

5. Conclusions

We further studied the performances of two-phase cryogenic detectors of ionizing radiation based on GEM structures and operated in an avalanche mode in Kr.

Stable operation of the triple-GEM multiplier in saturated Kr vapor, above the liquid, has been demonstrated for a few hours.

The signals induced by 0.5 MeV γ-rays were recorded from the two-phase detector in coincidences with a BGO counter, aiming at PET applications.

Charging-up effects were observed in GEM-based two-phase detectors at gains and anode current densities exceeding 200 and 10 pA/mm^2 respectively.

In a pulse-counting mode, the maximum gain of the triple-GEM in two-phase Kr could not exceed 1000. Such a gain value is enough for PET applications, but probably is too small for dark matter and coherent neutrino scattering experiments, where the primary ionization signal is by two orders of magnitude lower than that in PET. Therefore the ways to increase the gain of GEM structures in two-phase avalanche detectors should be looked for.

The results obtained are relevant for developing cryogenic two-phase detectors using heavy noble liquids, namely in the field of dark matter search, coherent neutrino scattering and PET. Further studies of this technique are on the way.

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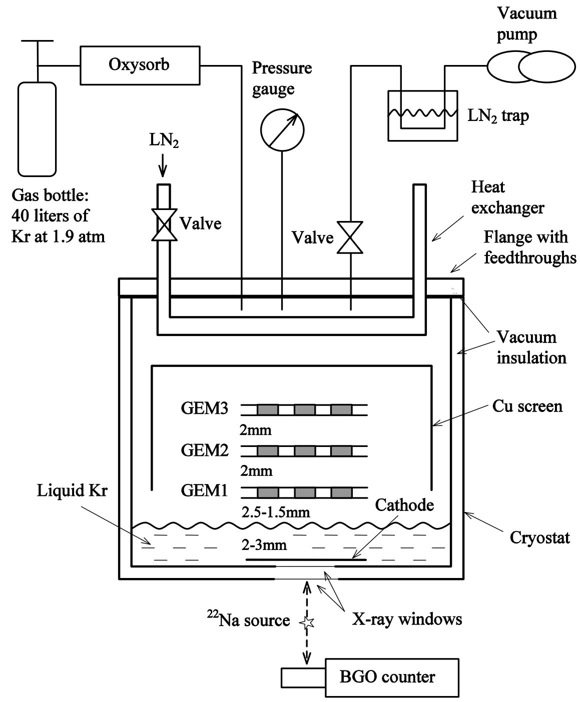

Fig.1 Schematic view of the GEM-based two-phase avalanche detector.

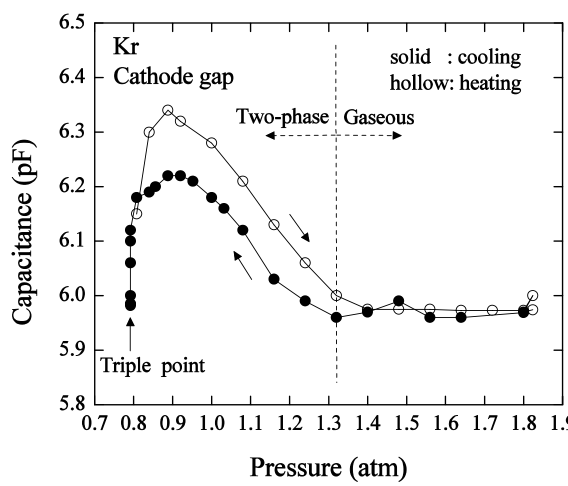

Fig.2 Formation of the liquid Kr layer during cooling and heating procedures. The cathode gap capacitance (between the cathode and GEM1) is shown as a function of the gas/vapor pressure.

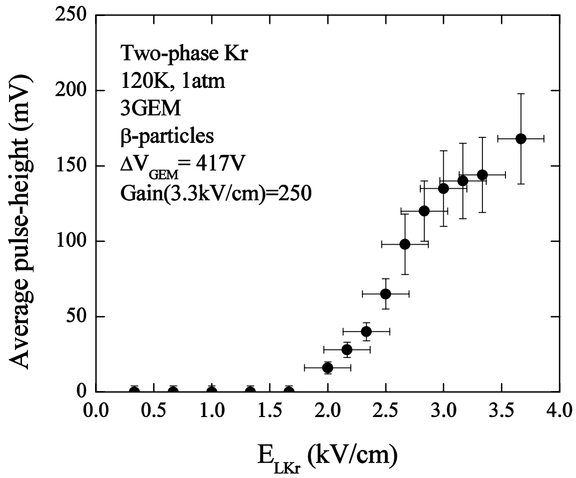

Fig.3 Electron emission from the liquid into gas phase. Average anode pulse-height from the triple-GEM in two-phase Kr is shown as a function of the electric field in liquid Kr.

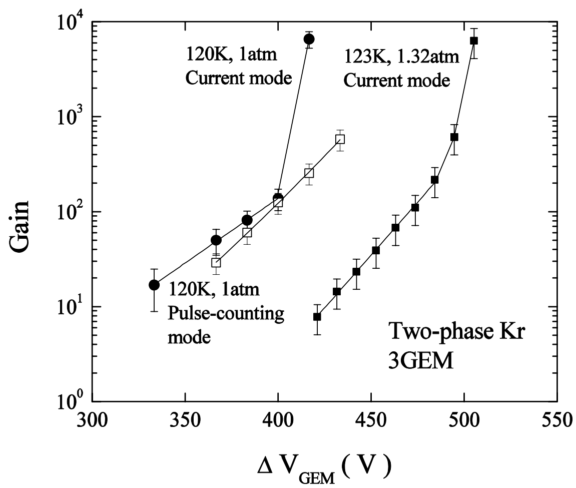

Fig.4 Triple-GEM gain as a function of the voltage across each GEM in two-phase Kr in a current and pulse-counting mode. The signals are induced by X-rays and β-particles, respectively. The maximum gains are limited by discharges.

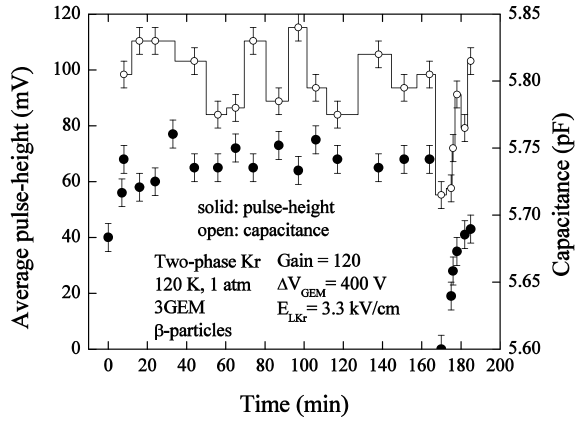

Fig.5 Stability of operation of the GEM-based two-phase Kr detector, at a gain of 120. Anode pulse-height from the triple-GEM, averaged over 8 pulses, and capacitance of the cathode gap are shown as a function of the time.

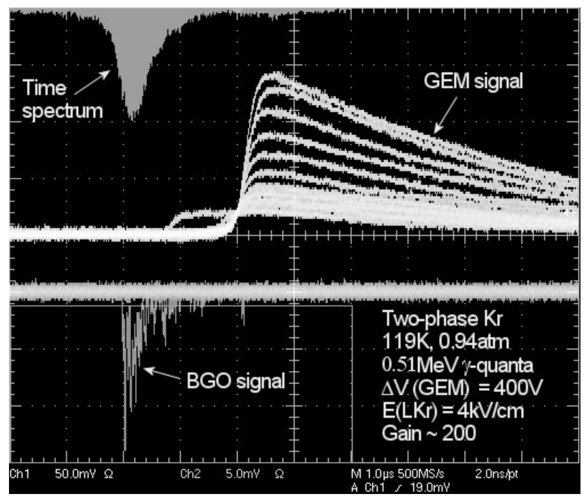

Fig.6 Anode signals from the triple-GEM at a gain of 200, a signal from the BGO counter and time delay spectrum of BGO signals with respect to GEM signals. The events are triggered by GEM signals using signal-above-threshold technique. The signals are induced by 0.51 MeV γ-rays from a ^{22}Na source.

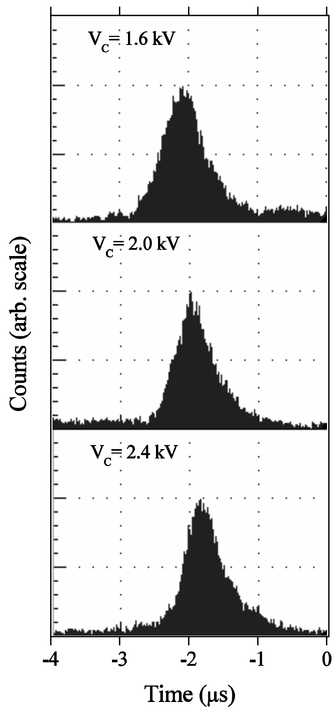

Fig.7 Time delay spectra of BGO signals with respect to GEM signals, at different cathode voltages.

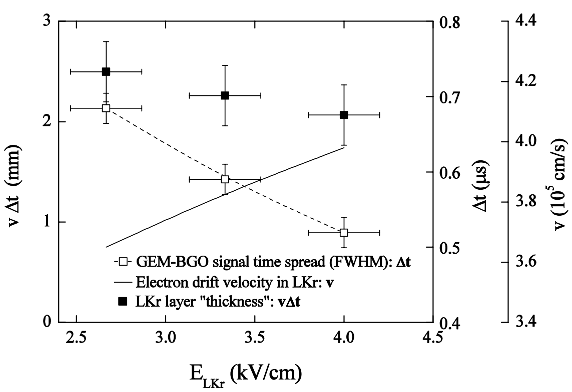

Fig.8 Estimation of the liquid Kr layer thickness, using time delay spectra. GEM-BGO signal time spread (FWHM), electron drift velocity in liquid Kr [14] and lower estimation of the liquid layer thickness are shown as a function of the electric field in the liquid.