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TRIPLE GEM OPERATION
IN COMPRESSED He AND Kr

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Abstract

We study the performance of the triple GEM (Gas Electron Multiplier) detector in pure noble gases He and Kr at high pressures, varying from 1 to 15 atm. The operation in these gases is compared to that recently studied in Ne, Ar and Xe. It turned out that light noble gases, He and Ne, have superior performance: the highest gain, approaching 10^5 , and the unusual gain dependence on pressure. In particular, the maximum gain in He and Ne does not decrease with pressure, in contrast to Ar, Kr and Xe. These results are of high relevance for understanding basic mechanisms of electron avalanching in noble gases and for applications in cryogenic particle detectors, X-ray imaging and neutron detectors.

Keywords: Gas Electron Multipliers; noble gases; high pressures.

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1 Introduction

There is the growing interest in developing gas avalanche detectors capable of operating in pure noble gases in a wide pressure range. On one hand, this interest is induced by the development of sealed gas photomultipliers [1,2], filled with pure noble gases. Such a filling should prevent the photocathode degradation under avalanche conditions.

On the other hand, this interest is motivated by recent suggestions to employ light noble liquids He and Ne and heavy noble liquid Xe as detection media for solar neutrinos [3] and dark matter [4], correspondingly. A detector of choice might be a double-phase device, where the ionization produced in liquid by a particle is detected in a gas phase with the help of the Gas Electron Multiplier (GEM) [5] operated at cryogenic temperatures. GEM-based detectors are particular promising for these applications due to the recently discovered capability of multi-GEM structures to operate in pure noble gases at high gains [6].

It should be remarked that the operation at cryogenic temperatures and atmospheric pressure could be equivalent to that at room temperatures and high pressures. Indeed, the gas density is a reciprocal function of the temperature at a given pressure and just the gas density is the parameter defining electron avalanche characteristics. Little is known, however, about GEM performance at high pressures [7,8] and in particular in compressed pure noble gases. So far, all investigators observed that the maximum GEM gain rapidly decreased with pressure.

Recently, we have studied the operation of the triple GEM detector in Ne, Ar and Xe [9] in the pressure range of 1 – 10 atm. The interesting observation was that Ne showed quite different pressure dependence of gain characteristics as compared to Ar and Xe, indicating that the gas amplification mechanism in light noble gases may change at high pressures.

In this work, we further study the performance of the triple GEM detector in other two noble gases, He and Kr, at high pressures reaching 15 atm. It is confirmed that the operation in light noble gases makes substantial difference to that of heavy noble gases: the performance in He and Ne turned out to

be superior in terms of gain-voltage characteristics and their dependence on pressure. Possible explanation for such behaviour is presented.

2 Experimental setup and procedure

The experimental setup and procedure were similar to that used in [9] (see Fig.1). Three GEM foils (50 μm thick Kapton, 80 μm hole diameter at a 140 μm pitch, $28 \times 28 \text{ mm}^2$ active area) and a printed-circuit-board (PCB) anode were mounted in cascade inside a stainless-steel vessel. The GEMs were produced at CERN workshop. The drift gap (between the cathode and the 1st GEM), transfer gaps (between the GEMs) and induction gap (between the last GEM and the anode) were 3, 1.6 and 1.6 mm, respectively. The detector was filled with He, Ne, Ar, Kr or Xe of a purity of 99.99%; it could safely operate at high pressures reaching 15 atm.

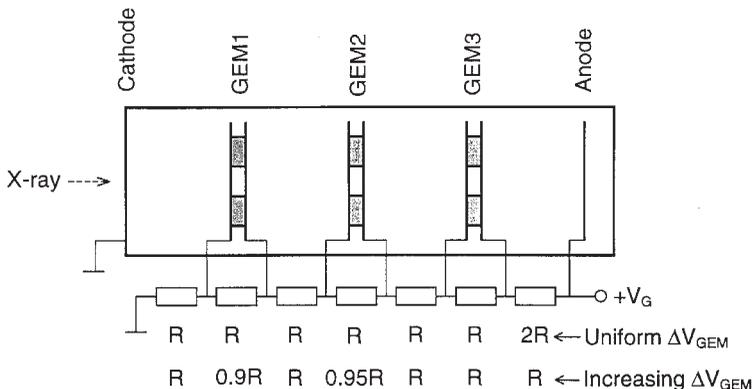


Figure 1: Schematic view of a triple GEM detector. Two voltage dividers were used, symmetrical and asymmetrical, with the uniform and increasing GEM voltage, correspondingly.

The detector was irradiated with an X-ray tube, with a molybdenum target, through a 1 mm Al window. The voltage and current supplied to the tube were in the range of 20 – 30 kV and below 60 μA , correspondingly. At these voltages the tube radiation is mostly peaked at molybdenum characteristic lines Mo K_α at 17.4 keV and Mo K_β at 19.7 keV. In Ne, Ar, Kr and Xe the primary ionization in the drift gap is produced by a photoelectric absorption of X-ray photons in gas molecules, while in He it is produced by

an X-ray-induced secondary electron emission from the GEM electrode. The latter process will be discussed in more detail in sect. 4.

GEM electrodes were biased through a resistive high-voltage divider, as shown in Fig.1. Two voltage divider configurations, symmetrical and asymmetrical, were used. The dividers were optimized in such a way as to obtain the maximum gain in an appropriate gas. In the asymmetrical divider, the voltage across a single GEM increased successively, by 5%, towards the last GEM. In the symmetrical divider, the voltage across each GEM was uniform; in addition, the voltage across the induction gap was doubled compared to that of the asymmetrical configuration. The symmetrical divider was effective for operation in He, while the asymmetrical divider was more effective in Ar, Kr, and Xe.

In He at 1 atm, typical electric fields were $E_D \approx 0.6$ kV/cm in the drift gap, $E_T \approx 1.1$ kV/cm in the transfer gaps, $E_I \approx 2.2$ kV/cm in the induction gap; the voltage across a single GEM ("GEM voltage") was $\Delta V_{GEM} = 150 - 200$ V. In Kr at 1 atm, the appropriate values were $E_D \approx 1.0$ kV/cm, $E_T \approx 1.9$ kV/cm, $E_I \approx 1.9$ kV/cm, $\Delta V_{GEM} = 250 - 350$ V.

The anode signal was recorded either in a current or pulse-counting mode. The anode current value was always kept below 100 nA, by reducing the X-ray tube intensity, to prevent charging-up of GEM foils. The maximum attainable gain was defined as that at which no anode current instabilities (dark currents or discharges) were observed for about 1 min.

In the current mode, the gain value of the triple GEM detector was defined as the anode current normalized to the current induced by primary ionization in the drift gap. The latter current was determined in special measurements, where the drift gap was operated in an ionization collection mode.

In the pulse-counting mode, the gain value was determined with the help of a calibrated charge-sensitive amplifier (with a sensitivity of 6 V/pC): the anode charge was divided by the primary ionization charge produced in the drift gap. The latter charge was calculated using the data on X-ray absorption in an appropriate gas.

3 Detector performance in Kr

Fig.2 shows gain-voltage characteristics of a triple GEM detector in Kr, at different pressures, for symmetrical and asymmetrical divider configurations. One can see that the asymmetrical divider, with increasing GEM voltage towards the last GEM, allows for reaching somewhat higher gains at high pressures.

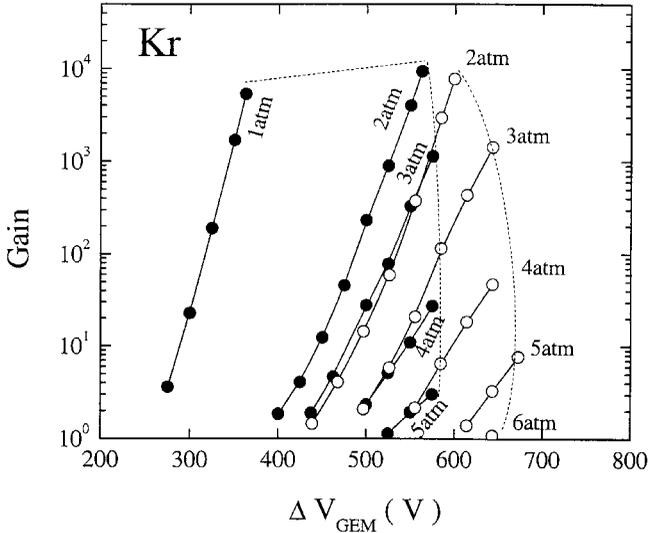


Figure 2: Gain of a triple GEM detector in Kr as a function of the voltage across the last GEM at different pressures, in a current mode. Two data sets are shown, for the symmetrical (solid points) and asymmetrical (open points) voltage divider.

It should be noticed that in multi-GEM detectors using gas mixtures with molecular additives, the optimized voltage divider had the opposite direction of the GEM voltage increment, namely towards the 1st GEM [10]. This is probably because of the specific nature of the discharge mechanism in noble gases: in noble gases the discharges are presumably generated by ion feedbacks from the last to preceding GEMs [6], due to an enhanced ion-induced electron emission as compared to other gases [11]. Decreasing the 1st GEM voltage would reduce this emission. Discharge phenomena in noble gases will be discussed in more details elsewhere.

In general, gain behaviour in Kr is very similar to that of Xe [9]: the maximum gain does not exceed 10^4 , weakly depending on pressure below 2 atm; at higher pressures it rapidly drops down to below 10 at 5 atm. Moreover, similar to Xe, the operation in Kr turned out to be much more sensitive to discharges, compared to He, Ne and Ar. All three GEMs could be destroyed after even a few discharges when operating in Kr or Xe at maximum gains in the pressure range of 1 – 2 atm.

4 Detector performance in He

In Ne, Ar, Kr and Xe the primary ionization is generated by photoelectrons ejected from gas molecules due to X-ray photon absorption. In He, however, the X-ray absorption in gas is suppressed due to an extremely small absorption coefficient. This was confirmed by the following observation: in He the primary ionization current in the drift gap was practically independent on pressure, in contrast to other gases.

Apparently, the ionization in He is produced by an X-ray-induced secondary electron emission from solid. A typical depth of a solid from which a secondary electron can be emitted is rather small: of the order of 10 atomic monolayers [12]. Nevertheless the estimations show that this layer is thick enough to provide the signal. The secondary electrons are emitted into the drift gap from the copper GEM electrode rather than from aluminium cathode, since the photon absorption in Cu is by a factor of 30 larger than in Al. The absorption of characteristic Mo K_α and Mo K_β photons in the Cu K-shell would result in ejection of photoelectrons having characteristic energies 8.5 keV and 10.7 keV, which are just the difference between the photon and

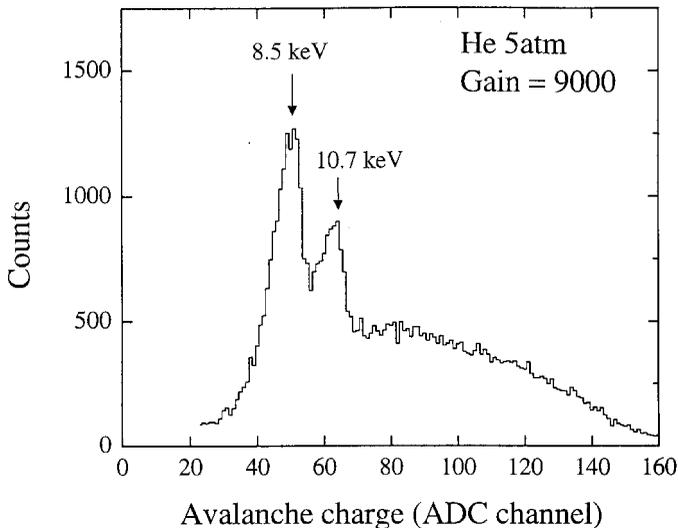


Figure 3: Pulse-height distribution of anode signals in He at 5 atm, at a gain of 9×10^3 . Two peaks correspond to photoelectrons ejected from the Cu K-shell due to absorption of Mo K_α and Mo K_β characteristic photons.

K-shell energies. If the rest of the absorbed energy escapes the detection, one would expect to detect two peaks in the energy distribution.

We indeed observed two peaks when operating in a pulsed-counting mode. Fig.3 shows the anode pulse-height distribution in He at 5 atm at a gain of 9×10^3 . The relative peak positions well correspond to photoelectron characteristic energies. The more energetic part of the spectrum is presumably produced via Auger process, when the rest of the absorbed energy is released by ejection of additional electrons.

For each peak, one can estimate a total number of ion pairs created in the drift gap, in He, and thus calculate the detector gain, dividing the anode charge by this number. It is interesting that the energy resolution in He, estimated from the width of the peak, is close to that obtained with multi-GEM detectors in other, traditional gas mixtures [13]: $\sigma/E \approx 10\%$ at 8.5 keV.

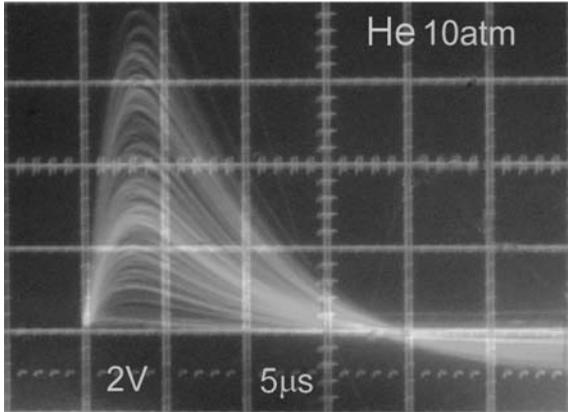


Figure 4: Anode signals in He at 10 atm, at a gain of 8×10^3 , detected with a charge-sensitive amplifier.

The signal shape supports our model for primary ionization production in He. Fig.4 shows anode signals after a charge-sensitive amplifier in He at 10 atm at a gain of 8×10^3 . A strong line in the middle of the scale is distinctly seen, obviously corresponding to escape peaks considered above.

Gain-voltage characteristics in He at different pressures are shown in Figs. 5 and 6, in a current and pulse-counting mode respectively. A symmetrical voltage divider, with an enhanced induction field, was used in these measurements. Comparing two measurement techniques, one may conclude that they

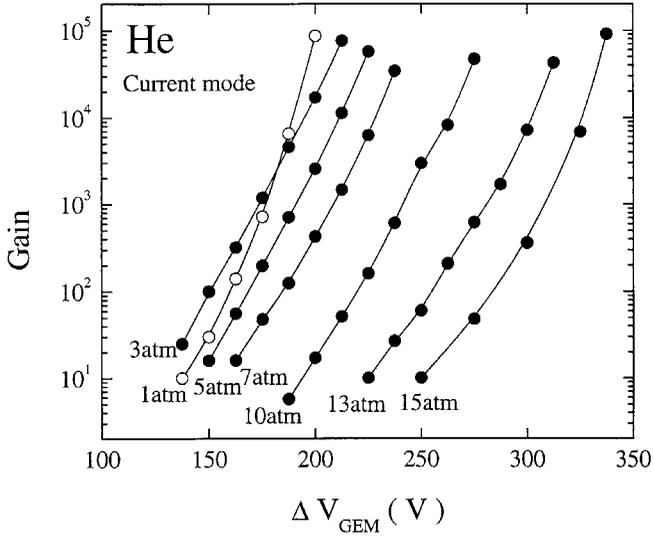


Figure 5: Gain of a triple GEM detector in He as a function of the voltage across each GEM at different pressures, in a current mode.

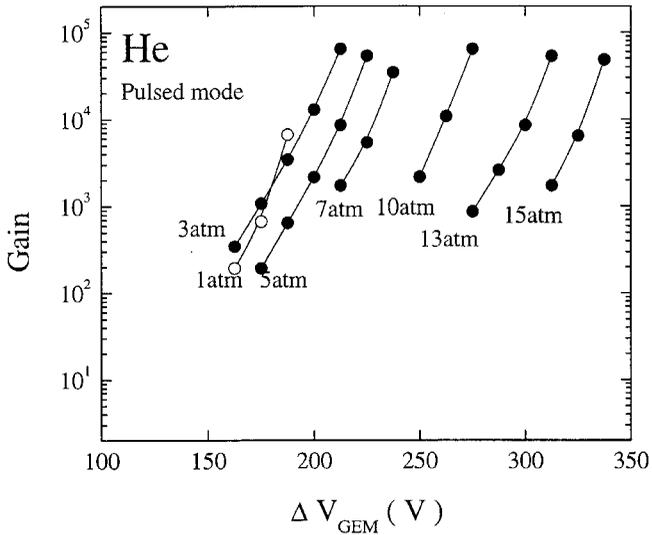


Figure 6: Gain of a triple GEM detector in He as a function of the voltage across each GEM at different pressures, in a pulse-counting mode.

both give similar results and that the measurement uncertainty of the gain is within a factor of 2. The maximum gain in He weakly depends on pressure, reaching a value of 10^5 at 15 atm.

Normally it is expected that the operation voltage of a gas detector substantially increases with pressure, following E/p scaling behaviour. This indeed was observed in heavy noble gases [9]. However, this was not the case in He and Ne. In He, in the pressure range of 1 – 7 atm, the operation voltage almost did not grow with pressure, increasing by 10% only. Moreover, in the range of 1 – 3 atm the operation voltage even decreased with pressure, at the initial part of the gain curve. To our knowledge, such unusual pressure dependence has never been observed before. This behaviour is very similar to that observed in Ne, where the operation voltage did not vary with pressure above 5 atm [9].

It should be noticed that the slopes of the gain curves are the same at all pressures, except of the data at 1 atm at the final part of the curve. The explanation is that at 1 atm the induction field was so high that it gave rise to a parallel-plate amplification mode in the induction gap, resulting in stronger gain dependence on voltage. The commencement of the parallel-plate mode

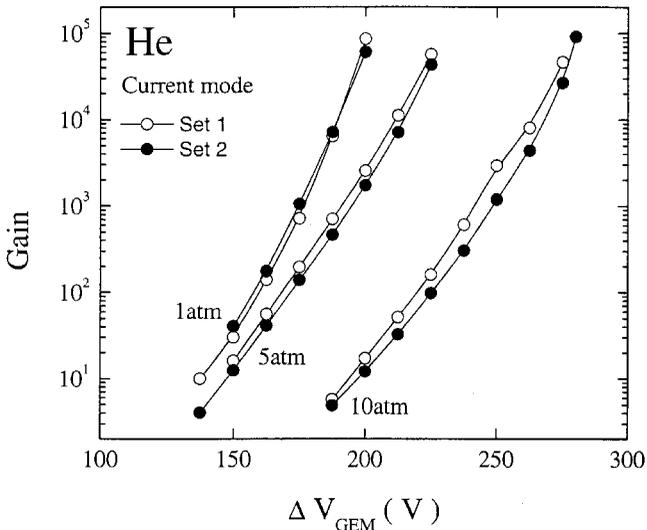


Figure 7: Data stability test in He. Two sets of gain-voltage characteristics are shown for two different triple GEM detectors and different air impurities, of the order of 10^{-4} (open points) and 10^{-6} (solid points).

at 1 atm was also indicated by transformation of the anode signals: the pulse-height distribution became exponential. The parallel-plate mode was not observed at higher pressures.

We checked the data stability, replacing the triple GEM detector for another one and adding a controlled amount of ambient air to He: of the order of 10^{-4} and 10^{-6} . This is illustrated in Fig.7 showing the comparison of two sets of gain characteristics. The impurity test is of particular importance, since one should exclude from consideration the avalanche mechanism induced by impurities such as Penning effect. One can see that data are well reproduced.

5 Discussion

Fig.8 shows the dependence of the maximum gain of a triple GEM detector on pressure in all the gases studied. The difference between light (He, Ne) and heavy (Ar, Kr, Xe) noble gases is clearly seen. Together with the unusual behaviour of gain-voltage characteristics in He and Ne, this may indicate that a new avalanche mechanism arises at high pressures in light noble gases, other than the electron impact ionization.

We propose that this mechanism is the associative ionization [11]. In the associative ionization, the electron is produced in atomic collisions due to the association of an atom with an excited atom into a molecular ion: $\text{He} + \text{He}^* \rightarrow \text{He}_2^+ + e^-$. The energy threshold for this reaction is lower than that of impact ionization. In addition, the contribution of the associative ionization should increase with pressure faster than that of impact ionization, since its reaction rate is proportional to the square of the gas density. The detailed analysis of experimental results from this point of view will be presented elsewhere.

If to believe that the gas density is the principle parameter defining avalanche characteristics in noble gases, the most effective operation of the multi-GEM detector would occur, at atmospheric pressure, at the following temperatures (derived from Fig.8): in Xe and Kr at 150 K, in Ar at 100 K, in Ne at 30 K and in He below 20 K. One can see that these temperatures are close to boiling points of the appropriate gas, speaking for that the GEMs could be successfully incorporated into double-phase cryogenic particle detectors.

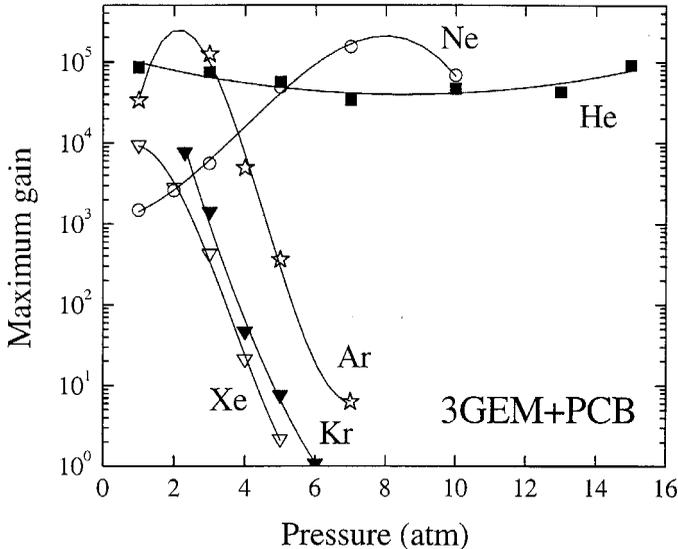


Figure 8: Maximum gain of a triple GEM detector as a function of pressure in He, Ne, Ar, Kr and Xe.

6 Conclusions

We have studied the operation properties of a triple GEM detector in pure He, Kr and other noble gases at high pressures, varying from 1 to 15 atm. Light noble gases, He and Ne, provided a superior performance: the highest gain, approaching 10^5 , and remarkable gain dependence on pressure. The energy resolution of the triple GEM detector in compressed He was measured to be about 10% at 8.5 keV, which is close to that obtained in traditional gas mixtures.

In Ar, Kr and Xe the maximum gain rapidly drops down for pressures exceeding 3 atm. In contrast, the maximum gain in He and Ne does not decrease with pressure. In addition, gain characteristics in He and Ne have an unusual pressure dependence: in a wide pressure range the operation voltage does not increase with pressure; moreover it can even start to decrease with pressure.

These results may indicate that a new avalanche mechanism starts playing a role at high pressures in light noble gases. We propose that this mechanism

is the associative ionization: at higher pressures it takes over the electron impact ionization due to stronger dependence on pressure and lower energy threshold.

The obtained results are of high relevance for applications in cryogenic detectors for solar neutrino and dark matter search, where the operation of avalanche detector in noble gases at high gas densities is needed.

Other possible applications follow from the results obtained in compressed He: we have actually demonstrated the successful operation of a secondary electron emission detector with a multi-GEM multiplier. The high gain, good energy resolution and insensitivity to the direct ionization of the gas by X-rays of such a detector are very attractive for X-ray imaging and neutron detection with solid convertors [14]. Another apparent application is a neutron detector using He^3 at high pressures, where He^3 would act as both a detecting and amplifying medium. Moreover, the adoption of non-ageing noble gas as an amplifying medium offers a big advantage, since it allows for operation in a sealed mode.

Further studies of this technique, e.g. GEM operation in pure noble gases at cryogenic temperatures, in a gas and liquid phase, at pressures higher than 20 atm, etc., are in course.

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