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ON THE LOW-PRESSURE OPERATION OF MULTISTEP AVALANCHE CHAMBERS

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ABSTRACT

It is demonstrated that in the double-step parallel-plate structure filled with pure low-pressure isobutane or methane, the gas preamplification-and-transfer mechanism occurs with an efficiency close to 100%, probably due to the electron diffusion process. Amplification in successive steps in isobutane and methane at pressures of 2–10 Torr is shown to be possible. An increase in total gain of 10–80 as compared to maximum amplifications attainable in a single-step structure is observed with 5.5 MeV alpha particles and single electrons. The possible applications of multistep low-pressure counters for single-electron (photoelectron) imaging are discussed.

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1. INTRODUCTION

The idea behind our attempt to test multistep avalanche chamber structures at low gas pressures was to try to increase the maximum attainable gain of low-pressure detectors in view of their applications to single-electron detection and imaging. Low-pressure gaseous detectors, widely used for the detection of heavily ionizing particles, have been proved to detect efficiently single electrons [1]. They have several advantages in comparison with detectors operating at normal gas pressures, in cases where the detection process does not rely on direct ionization of a gas by charged particles but on secondary electrons produced by a photoelectric effect on photocathodes or in photosensitive gases:

- i) High extraction efficiency of photoelectrons from a photocathode surface to a gas, due to an increased reduced electric field E/p at the cathode surface.
- ii) High gains of up to 10^7 [1] obtained in pure hydrocarbons, resulting in a saturated avalanche response for a single electron.
- iii) Subnanosecond time resolution.
- iv) Very low sensitivity to relativistic charged particles and to low-energy gamma rays, due to low gas density.
- v) High counting rate capability [2], due to much faster drift velocities of positive ions in the high reduced fields resulting in the reduction of space charge and in short electronic occupation time. (Examples of the fast ion-collection times are shown in fig. 1.)

Detectors such as parallel-plate avalanche chambers (PPACs) or multiwire proportional chambers (MWPCs), operating at pressures of a few Torr, are at present used as single-electron detection and imaging devices coupled to solid [3,4] or liquid [5] photocathodes for photon-detection applications.

Multistep avalanche chambers (MSACs) [6] have been proved to be successful detection devices at normal gas pressures for minimum ionizing particles at high rates [7] and as photosensitive detectors for UV photons in Čerenkov ring imaging [8].

The preamplification of an initial charge and the transfer of the primary avalanche to a second amplification step, as shown in fig. 2, have been the subject of an intense study during the last few years [6,7,9,10]. Using pure electrostatic considerations it was proved that an efficient charge transfer from the preamplification region to the transfer region ($E_p \gg E_t$) can only occur if the avalanche has a lateral spread of the same order as or exceeding the wire spacing of electrode b [6]. At normal pressures and with standard gas mixtures the electron diffusion, in a simple avalanche model, is often too small to allow an efficient transfer. Extended photon-mediated avalanches can be obtained in some binary gas mixtures, similar to the one used in Geiger counters, where the ionization potential of one of the molecules is lower than the energy of the excited state of the other atom or molecule [6]. At low gas pressures electron diffusion leads to wide avalanches [11] and we show that the multistep operation can take place efficiently even in organic gases such as isobutane or methane, with an increase in total gain of 10–80 compared to single-step operation.

Several of the interesting features of MSACs may be of importance for the application to single-electron detection:

- i) Higher amplification in comparison with a single-step PPAC or a MWPC.
- ii) Gating possibility on selected events that offer a better counting-rate capability [7].
- iii) Reduction of the photon feedback mechanism at the cathodes and in the gas, since photoelectrons produced by photons coming from the avalanche are absorbed in the transfer region and are not subject to the full two-step amplification.

- iv) A possibility of reducing the positive-ion feedback effect on the cathodes by stopping backward going positive ions with a gating electrode.
- v) Unambiguous read-out of multiple events with multielectrode structures by passing the avalanche electrons through successive electrodes that have wires oriented in various directions [6].

In the present work we show the first results of the low-pressure operation of MSACs and discuss possible applications.

2. EXPERIMENTAL CONDITIONS

We have studied the operation of two different double-step structures. In both cases the first step is a 3.3 mm thick parallel-plate detector with its anode made out of stainless-steel 50 μm diameter wire mesh, with a cell size of 500 μm , and an 8.4 mm thick transfer region followed by an electrode made of the same kind of mesh. The second amplification step is either a 3.3 mm thick parallel-plate counter or a multiwire chamber having a 2×3 mm gap with 10 μm diameter anode wires 1 mm apart. Since both structures show very similar behaviour, only that concerning the double-step avalanche chamber is presented in this work.

The measurements were performed at pressure values of 2–10 Torr of isobutane and methane. The detectors were operated either with a ^{241}Am source, placed inside the chamber, providing 5.5 MeV α -particle tracks perpendicular to the detector surface, or with single photoelectrons produced at the first cathode (the cathode of the first PPAC) by UV photons. The UV photons from an external light source entered the chamber through a CaF_2 window.

3. EXPERIMENTAL RESULTS

Our first aim was to check if an electron swarm can be efficiently transferred from a first preamplifying step to the second step at a low gas pressure. We found that in both gases tested an efficient transfer mechanism takes place. The transfer efficiency is shown in fig. 3 for single electrons in a double PPAC structure filled with isobutane at 5 Torr. The upper oscilloscope trace shows electronically shaped pulses from the first stage, the lower one from the second stage (electrodes a and d respectively, from fig. 2). The time base was triggered by the pulses from the first step. As is seen, the efficiency of the transfer is close to 100% (a small effect of missing pulses can be explained by edge effects due to lack of precise collimation of the UV-photon beam). It means that for each avalanche produced in the first PPAC a substantial part of the electron cloud is transferred to the following region of a lower electrostatic field. The electrons are then transferred to the second amplifying step, where the electrical field is higher. The main condition required for a proper transfer mechanism is that the transversal size of an avalanche produced in the preamplifier step should be larger than the wire mesh spacing (500 μm in our case) of electrode b. It is likely that the reason for the broad size of avalanches in low-pressure isobutane (1–2 mm FWHM [11]) is related to electron diffusion at low pressures.

We have proceeded to search for the optimum operating conditions, trying to reach higher amplifications than in a single-step structure. Our first observation is that in a pressure range of 2 to 10 Torr, isobutane works much better than methane. The highest gains were achieved with isobutane at a pressure of about 5 Torr. In methane reasonable amplification factors, though lower

than with isobutane, could be reached only above 10 Torr. In all cases we have observed an increase in the total gain in the double structure as compared with the single structure. This gain improvement factor was variable and could reach up to the 80, depending on the operating conditions. Apart from the pressure dependence it was found that the maximum possible gain in a double-step structure increases when the electric field strength in the transfer region is decreased. Assuming that the spark limit at given conditions is related to a space-charge density in an individual avalanche in the second detector step, one can explain the observed effect by an enhancement of the lateral avalanche size due to diffusion of electrons drifting in the transfer region. Another interpretation can be related to reduction of positive-ion feedback; there is a limit of amplification due to positive-ion feedback at the cathode of the first step, and the percentage of ions moving back to the first stage is about linearly dependent on the field intensity in the transfer region if the other parameters are kept constant.

3.1 Results of measurements in isobutane

Figure 4 shows the amplification curves for two extreme values of the transfer field E_t . The total gain is increased by almost two orders of magnitude at the low transfer field; notice the limit of amplification of a single-step PPAC shown in the figure. Examples of charge pulses taken at 5 Torr with α -particles in a single step and a double step operating with a transfer field of $2 \text{ V} \cdot \text{cm}^{-1} \cdot \text{Torr}^{-1}$ are shown in fig. 5. Current pulses of α -particles in the double-step mode are shown on fig. 6. In fig. 7 are presented two spectra obtained at 5 Torr in a two-step structure, measured on electrodes a and d (fig. 2) with single photoelectrons. The saturated response is observed in both stages. At the reduced transfer field of about $2 \text{ V} \cdot \text{cm}^{-1} \cdot \text{Torr}^{-1}$ the two-step amplification is about 30 times higher than the maximum amplification attainable in a single step. At a pressure of 10 Torr, the double-step gain increase is only of about 10. At this pressure and with a reduced field of $2 \text{ V} \cdot \text{cm}^{-1} \cdot \text{Torr}^{-1}$ the chamber gets into a “very high amplitude” mode with pulses reaching 1 mA peak current (fig. 8). We have not explored further the properties of this “magic” mode of operation.

At 2 Torr a gain increase factor of about 30 was obtained in a wide range of reduced transfer fields from 3 to $30 \text{ V} \cdot \text{cm}^{-1} \cdot \text{Torr}^{-1}$. The drift velocity of positive ions is already so high that one cannot distinguish between electronic and ionic components of a pulse (fig. 1a). The absolute amplification in a single step is limited by positive-ion feedback, clearly visible in fig. 9.

3.2 Measurements in methane

In methane, as was already mentioned, the low amplification limit in the range of pressures from 2 to 10 Torr is due to secondary processes at the cathodes. The strong positive-ion feedback mechanism in the two-step PPAC structure at 2 Torr is shown in fig. 10 for single photoelectrons. Figure 11 shows the same phenomenon in the same structure, but at 4 Torr for α -particles in the cases of a weak and a strong transfer field. The observed difference in the feedback time constants is due to the different drift velocity of positive ions in the two cases. In a single-step structure we could also observe the photon feedback mechanism, as can be seen in the oscilloscope picture of fig. 12 (appearing there as an after-pulse). In contradiction with these results, in a short measurement done at 20 Torr we have observed much better operation and safely attained high amplifications. The effect of the higher pressure is probably in slowing down methane positive ions of high mobility and then in limiting their efficiency of secondary emission when striking a cathode. A gain increase factor of 2–3 at most was found in these conditions, which could mean that methane is not a good choice for a double-step structure.

4. SUMMARY AND POSSIBLE APPLICATIONS

With these first results we have demonstrated that a double-step process is possible in low-pressure gases, most probably due to electron diffusion in the first amplification process. In the case of low-pressure isobutane one can achieve excellent performances with very high amplification factors of up to 10^7 . The double-step structure enables one to gain 1 to 2 orders of magnitude in the total amplification factor. The "very high amplitude" mode obtained in isobutane should be further investigated because of possible advantages of operation with saturated amplitudes.

One could envisage several future applications of low-pressure multistep detectors based mainly on their high amplification, their insensitivity to relativistic particles, and their imaging and gating capabilities. The gating could be fast or slow: fast, when avalanches produced in the first stage are allowed to enter the second amplification region only if an electronic gate pulse is applied; slow, when one wants to prevent positive ions from reaching the cathode. This could be used in the case of gas photodiodes filled with methane or isobutane, when positive ions destroy the alkali photocathode [3]. The idea in this case will be to close a gate each time after an electronic pulse is detected and recorded.

One could think of another specific application of such a structure in d.c. and gated operation for Čerenkov ring imaging either with photosensitive gases or liquid photocathodes. The vapour pressure of the presently used photosensitive compound tetrakis(dimethylamine)ethylene (TMAE) added to the main gas is very low even at room temperature (0.35 Torr at 20°C) [12]. One could work with very low pressures of gas, preserving the same quantum efficiency while the chamber is insensitive to passing charged particles and having all the other above-listed advantages of low-pressure double-step detectors.

Some other studies of low-pressure double-step parallel-plate structures, or parallel-plate counters followed by MWPCs, were also independently performed for heavy ion applications [13,14].

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Figure captions

- Fig. 1 Examples of α -particle pulses, after a charge-sensitive preamplifier, in a single-step structure filled with low-pressure isobutane: upper trace (a) at 2 Torr, middle (b) at 5 Torr, and lower (c) at 10 Torr. Horizontal scale: 500 ns/div. Note the difference in the rise-time, corresponding to total ion-collection times. At 2 Torr the electronic and ion components of the pulse are confused.
- Fig. 2 A double PPAC structure used for the measurements. Preamplification and amplification regions are 3.3 mm thick and the transfer region is 8.4 mm thick. Electrode a is a copper plate, while all other electrodes are made out of 93% transparent stainless-steel mesh. α -particles' tracks from the ^{241}Am source are approximately perpendicular to the electrodes. A UV photon enters through a CaF_2 window and produces a photoelectron at the electrode, initiating a two-step avalanche. The initial avalanche can spread laterally in the transfer region owing to diffusion when drifting in a low electric field E_t .
- Fig. 3 Demonstration of the high efficiency of a double-step amplification process in 5 Torr of isobutane. Electronically shaped pulses from electrodes a (upper trace) and d (lower trace) from fig. 2, are displayed. The oscilloscope trace was triggered by pulses from the first step, electrode a. $E_p/p = 430$, $E_t/p = 4$, $E_a/p = 240 \text{ V} \cdot \text{cm}^{-1} \cdot \text{Torr}^{-1}$.
- Fig. 4 Amplification curves (electronic component, Q_{el} , only) measured with α -particles in a double PPAC detector filled with 5 Torr of isobutane. The curves were measured at a constant preamplification field of $330 \text{ V} \cdot \text{cm}^{-1} \cdot \text{Torr}^{-1}$ and with a variable E_a/p field of up to $230 \text{ V} \cdot \text{cm}^{-1} \cdot \text{Torr}^{-1}$. Two extreme cases were analysed with a very low ($E_t/p = 1 \text{ V} \cdot \text{cm}^{-1} \cdot \text{Torr}^{-1}$) and a high ($E_t/p = 50 \text{ V} \cdot \text{cm}^{-1} \cdot \text{Torr}^{-1}$) electric field in the transfer region. Notice the difference in the maximum attainable amplification factor (just before breakdown) in the two cases.
- Fig. 5 Examples of α -particle pulses from a charge preamplifier (ORTEC 124) in a single-step (upper trace, 5 mV/div and 500 ns/div) and a double-step (lower trace, 200 mV/div and 500 ns/div) structure in 5 Torr isobutane as measured directly on a $1 \text{ M}\Omega$ load. In the first case the detector was operated with an E_p/p value of $330 \text{ V} \cdot \text{cm}^{-1} \cdot \text{Torr}^{-1}$. In the second case the field values were as follows: $E_p/p = 330$, $E_t/p = 1.2$, $E_a/p = 305 \text{ V} \cdot \text{cm}^{-1} \cdot \text{Torr}^{-1}$. Notice the shape of the ion component in the double-step mode, corresponding to a saturated-gain mode.
- Fig. 6 Current pulses from α -particles measured directly on a 200Ω load in a double-step detector filled with 5 Torr of isobutane. $E_p/p = 330$, $E_t/p = 1.2$, and $E_a/p = 215 \text{ V} \cdot \text{cm}^{-1} \cdot \text{Torr}^{-1}$. Scales: 40 mV/div and 200 ns/div.
- Fig. 7 Pulse-height spectra of single photoelectrons as measured on electrodes a and d in the conditions specified in the caption to fig. 3. The spectrum measured at the electrode d was not gated by the pulses from the electrode a and many pulses of low amplitude are due to avalanches started by photoelectrons produced at the meshes b and c. The total increase in gain of the double-step structure is of the order of 30. The charge at the peak of the electrode d is about 3 pC.

- Fig. 8 Transition to the "high amplitude mode" in a double-step PPAC detector with 10 Torr of isobutane, measured with α -particles directly on a 200 Ω load. $E_p/p = 212$, $E_t/p = 2.5 \text{ V} \cdot \text{cm}^{-1} \cdot \text{Torr}^{-1}$. Horizontal scale: 500 ns/div. Photographs taken at 3 working points: a) normal proportional mode pulses, $E_a/p = 9 \text{ V} \cdot \text{cm}^{-1} \cdot \text{Torr}^{-1}$; vertical scale: 10 mV/div., b) $E_a/p = 18 \text{ V} \cdot \text{cm}^{-1} \cdot \text{Torr}^{-1}$; vertical scale 20 mV/div., c) $E_a/p = 27 \text{ V} \cdot \text{cm}^{-1} \cdot \text{Torr}^{-1}$; vertical scale: 100 mV/div. Notice the low amplification field in the amplifier region.
- Fig. 9 Example of an α -particle current pulse from a low-input impedance amplifier as observed at the limit of amplification in a single-step detector filled with isobutane at 2 Torr. $E_a/p = 750 \text{ V} \cdot \text{cm}^{-1} \cdot \text{Torr}^{-1}$. Horizontal scale: 500 ns/div.
- Fig. 10 Demonstration of the positive-ion feedback process taking place in a double-step PPAC counter in methane at 2 Torr. Differentiated single photoelectron pulses from a charge amplifier. $E_p/p = 680$, $E_t/p = 17$, $E_a/p = 36 \text{ V} \cdot \text{cm}^{-1} \cdot \text{Torr}^{-1}$. Horizontal scale: 20 $\mu\text{s}/\text{div}$.
- Fig. 11 The feedback mechanism as observed with single photoelectrons at the limit of amplification in a double-step detector with a 4 Torr methane filling. $E_p/p = 375 \text{ V} \cdot \text{cm}^{-1} \cdot \text{Torr}^{-1}$. Case a: $E_t/p = 4 \text{ V} \cdot \text{cm}^{-1} \cdot \text{Torr}^{-1}$. Case b: $E_t/p = 50 \text{ V} \cdot \text{cm}^{-1} \cdot \text{Torr}^{-1}$. Horizontal scale: 50 $\mu\text{s}/\text{div}$.
- Fig. 12 Photon-feedback mechanism as seen on a differentiated output pulse from a charge amplifier connected to the single-step counter filled with 4 Torr of methane. Horizontal scale: 200 ns/div.

Fig. 1

preamplification transfer amplification

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12