EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/87-219

2 December 1987

**STUDIES OF LIGHT EMISSION BY
CONTINUOUSLY SENSITIVE AVALANCHE CHAMBERS**

G. Charpak, W. Dominik, J.P. Fabre, J. Gaudaen, F. Sauli and M. Suzuki

CERN, Geneva, Switzerland

ABSTRACT

The optimal conditions for the optical recording of images of electron avalanches between parallel meshes have been studied.

The emission spectra of gas mixtures have been investigated, where triethylamine (TEA), tetrakis(dimethylamine)ethylene (TMAE), and nitrogen, are used as the photon-emitting agents.

For a given charge gain, the photon intensity decreases with electric field. This favours amplification between parallel meshes instead of wires. The use of intensified CCD cameras permits the recording of the local energy loss along the tracks.

(Submitted to Nuclear Instruments and Methods in Physics Research)

1. INTRODUCTION

In various articles [1–3] we have described the results obtained in gaseous detectors by optical imaging of the avalanches produced by electrons multiplying in a high electric field. These electrons are produced by ionizing reactions, and a very wide range of applications can be foreseen if the light produced by the molecules excited in the gaseous medium is sufficiently intense to be easily imaged.

In the last version of our detectors [3] (Fig. 1) the avalanches were produced between parallel grids, thus avoiding the delicate construction of wire planes and giving an isotropic response with respect to the orientation in the electrode plane. These gaps between the parallel grids can easily be arranged in successive layers for a multistep operation. This permits the detection of single photoelectrons and has been successfully used for Cherenkov ring imaging by charge-sensitive readout, with triethylamine (TEA) [4] as the photoionizable vapour. When the gaps are sufficiently wide, it is found that such chambers are free from photon feedback problems and permit gains above 10^6 to be easily reached. Similar results have also been found with tetrakis(dimethylamine)ethylene (TMAE) as the photoionizable gas [5].

However, we have observed that in order to detect minimum-ionizing particles at atmospheric pressure using optical readout, one single amplification step is enough, since the δ -rays along the tracks produce enough high-density ionization spots to give a good representation of the particle trajectory (as illustrated by Fig. 2), which is sufficient for many applications. However, for the imaging of avalanches produced by single electrons, the multistep operation would be necessary with our present optics and image intensifiers. As a consequence, we have oriented our research in several directions.

A charge-coupled device (CCD) camera located after the two-stage image intensifier has enabled us to exploit the dynamic range of the light-emission intensity, since this method has the precious property of displaying the local energy loss along the tracks. Using photomultipliers, we have compared the energy resolution of X-rays detected by charge collection and by light detection.

Our first satisfactory results have been obtained with TEA vapour mixed with various gases. This vapour emits photons in a spectrum centred at 280 nm, and we have shown that about one photon per electron is produced in an avalanche [3, 6, 7].

We have made a quantitative study of the emission spectrum of TEA mixed with some of the various gases that could be used in our detector. In order to facilitate the solution of optical problems, we orientated our efforts towards finding a vapour that emits in a spectral domain closer to visible light. We focused our interest on the properties of TMAE because of its importance as a low-threshold photoionizable vapour, and indeed found that it emits visible radiation ($\lambda > 400$ nm) when it is excited by electron avalanches.

However, TMAE is not very easy to handle, and we studied the conversion of the UV light emitted either by TEA alone, or by other gas mixtures not containing TEA or TMAE, in thin layers of a wavelength shifter (WLS) placed against the final anode grid. We found that this conversion is relatively simple and could considerably improve the light yield from a counter using TEA as the radiating vapour: in this case the shift in wavelength makes the light collection easier, thus enabling it to be improved by a factor of 20.

2. STUDY OF THE EMISSION OF LIGHT BY SOME GAS MIXTURES

We have used the device illustrated in Fig. 3: α -particles from an ^{241}Am source are stopped in a gas mixture. The ionization electrons are drifted by an electric field to a multiplying gap between two grids, which are either 1 mm or 1.5 mm apart according to which of the two versions of the device is being used. The photons emitted by the avalanche are analysed by a spectrophotometer or directly detected by a photomultiplier after traversal of a CaF_2 window. Figure 4 shows the photon spectrum

in a mixture containing TMAE vapour. The spectrum, peaked at about 480 nm, is in agreement with the fluorescence spectrum of TMAE vapour excited by UV photons (250–390 nm) [8].

The charge signals from the multiplying gap are analysed in parallel with the light signals. Using a charge preamplifier of 200 μ s decay constant, we measured the real charge gain $e^{\alpha d}$.

The emission of light as a function of gain reveals interesting features. In mixtures containing TEA or TMAE, we observe light emission before any multiplication occurs (Fig. 5). We can thus have gas scintillation produced by a drifting electron, as in pure noble gases. This observation has direct consequences on our detector and explains some of its features. We have seen that for the same charge gain in a counter with TEA or TMAE, we have a linear increase of photons commensurate with the gap size. We have also observed the same increase when there is no charge multiplication. If some scintillation light is emitted without ionization by atoms in the excited state, this is normal: for the same charge gain the ionization mean free path in the wider gap is longer, so that within this path there can be more inelastic collisions giving rise to scintillation light. We expect that the intensity of the scintillation photons will be proportional to the total voltage drop [7], which is larger in a wider gap. In the multiwire chambers with very thin anode wires, the electrons reach a high energy in a very narrow region around the wire, and the relative amount of excitation may be smaller. We found the parallel-grid structure, with wide gaps, to be the most favourable for photon emission, with the clear advantage of being isotropic in the plane of the chamber.

There is no proportionality between charge gain and photon gain (Fig. 6). The relative amount of light is variable between TEA, N₂, and TMAE. Light output is normalized to the unit of the primary charge in the drift space and corrected on the spectral sensitivity of the photomultiplier (bialkali photocathode on the quartz window). Because the spectral regions are different for these emitters—about 280 nm for TEA, 340 nm for N₂, and 480 nm for TMAE—the correction is necessary in order to make a proper comparison of the light yields. However, the experiments with TMAE were done at 23 °C, where the vapour pressure is only 0.3 Torr. Experiments with nitrogen added to argon (Fig. 6) show a very good light yield comparable to TEA. This gas, however, is not as favourable for electron multiplication.

3. USE OF AN INTENSIFIED CCD CAMERA

With respect to the set-up of Ref. [1], we simply changed the type of camera [9]. The image from the chamber is transferred to the first image intensifier via an objective F/4.5 for UV light or F/1 for visible light. The active section of our system is composed of two image intensifiers. The first one is a proximity-focused, single-stage diode of 25 mm photocathode diameter. It is essentially a wavelength converter with high quantum efficiency of the photocathode (bialkali) and relatively small gain (~ 20 photons per photon). The gain is achieved by electron acceleration in the high electric field between the photocathode and the phosphor screen-anode. The fast-X3 type phosphor is deposited on the fibre optics backplate, allowing a very efficient coupling to the next stage of the light intensification. The second stage is a multichannel plate image intensifier of 25 mm active diameter with an S20 photocathode and a P20 phosphor layer on the fibre-optics plate. This structure allows a gain of ~ 30000 photons per photon, thus making it the main light intensifier of the chain.

Since the CCD that we use has a diagonal (7 mm) smaller than the diameter of the backplate of the second image intensifier, we employ fibre optics taper for the CCD attachment to the system (in order to collect light efficiently without distortion of the image). This CCD (Thomson 7852 CDA-80) has 144 lines of 208 pixels; it produces a standard video signal which can be displayed on a monitor and fed to a digitizer card (Data Translation DT 2851) which interfaces to an IBM-PC/AT computer. This allows images produced by the chamber and viewed by the optoelectronic camera to be stored and analysed by the computer. In order to conserve disk space and to accelerate the storage

process, the images are compressed using a run-length-encoding algorithm. This algorithm replaces runs of identical pixel values by a single pixel value followed by its repeat count. In our case a typical compacted image takes about 15 kbytes. The digitizer has a precision of 8 bits, which allows an accurate measurement of the light intensity over a large dynamic range, thanks to the excellent linearity of the optoelectronic chain.

The light emitted by the avalanches is proportional to the primary charge, and from the computerized images we can expect information on the local energy loss.

If we compare the electric pulses from the charges collected on the anode grid with the light pulses from a photomultiplier viewing the chamber at a distance of 1 m, we indeed observe that the energy resolution is just as good in both cases (Fig. 7). With 5.9 keV X-rays, the spots that make up the image of each avalanche are between 1 mm and 2 mm wide, and the centroid—as we could verify using a well-collimated source—is accurate to within 250 μm (r.m.s.).

With α -particles the chamber displays some of its intrinsic qualities. We made the study using various gas mixtures. Figures 8a and 8b illustrate the pictures obtained with argon and helium, respectively, as the main gas carriers. The interesting thing is that the energy loss along the track reflects what is expected qualitatively from the Bragg curve. In Fig. 9 we have selected an event where the α -particle is scattered in the gas. The average ionization along the tracks is obtained from the CCD.

We have tried to observe tracks with TMAE with a single-step amplification in the device shown in Fig. 1, and the results confirm the relative scarcity of light. The tracks are very diffuse. But if we use a multistep structure with two parallel gaps separated by a transfer space of 25 mm, we observe cosmic-ray events (Fig. 10); this figure shows a heavily ionizing one. With TEA mixtures we had to use an UV objective of aperture 1/4.5, for reasons of availability. With the TMAE mixture the aperture was 1/1. The gain of nearly 20 partly compensates for the loss of light. Although one can build large-aperture optics for the TEA emission domain (but at a high cost), it is clear that the short wavelength is a limitation. For this reason we have concentrated our efforts on converting the UV light into visible light by using WLSs placed against the anode grid, thus making it possible to widen the choice of filling gases. The choice is dictated by the requirements of the physical application envisaged for the chamber.

4. CONVERSION OF UV LIGHT

The parallel-grid geometry is very convenient for the wavelength shifting of light very near to the emission point. The majority of the excited atoms are at a distance of a few ionization mean free paths from the last grid, i.e. a fraction of a millimetre. The loss of resolution due to the distance of these excited atoms from the light converter is thus small if the WLS is placed against the grid. We tested a well-known WLS: sodium salicylate. It was deposited on a Mylar foil and covered with a 50 μm thick Aclar^{*)} foil placed against the anode mesh of the amplification gap. The absorption length of our Aclar foil is 230 μm for photons between 250 and 350 nm. Such a WLS structure will separate the sodium salicylate powder from the detector gas. Sodium salicylate is known to convert photons in the 200–350 nm visible-light range with almost 100% efficiency [10]. The result is spectacular. With α -particles and a gaseous mixture containing TEA we could see the tracks with the naked eye, after only a few minutes for accommodating in the darkness.

We could record the tracks with a mixture containing only argon, methane, and nitrogen, without TEA (Fig. 11 shows an example of such a track).

^{*)} Aclar: polychlorotrifluoroethylene (PCTFE).

5. SOME APPLICATIONS

The fact that imaging with CCD cameras records the local energy loss brings great power to this readout method. No electronic readout can deliver such complete information on a pattern of energy deposition in a gas.

5.1 High-density detectors

With heterogeneous drift spaces, one can envisage that such detectors could be valuable candidates for proton decay studies. The quality of the pattern is very favourable for background rejection and particle identification. The local energy-loss information is an additional asset. We are preparing tests with a large-size detector, of 15 radiation lengths depth, in high-energy electron beams. Preliminary results without a CCD camera have given encouraging pictures [3].

5.2 Slow-neutron imaging detectors

Our experiments show that helium is a very convenient filling gas: ^3He could be used. The interesting point is that we could get a full image of the two prongs recoiling after the neutron absorption, thus determining the origin with an accuracy of a fraction of a millimetre. One could imagine a spherical drift chamber analogous to the one used for X-rays, filled with ^3He + TEA and another gas such as Ar or CH_4 in order to control, at will, the range of the recoil nuclei [11]. The electrons can be transferred to a multiplying gap between two grids. The recoil pattern would be preserved by the drifting, and there would be no parallax error because of the radial field in the drift space. Such a method would be slow since it requires image analysis by a computer, but it would have the unique properties of accuracy and noise rejection.

5.3 Liquid optical detectors

It has been shown [12] that it is easy to extract electrons from liquid TMP and amplify them between two parallel grids. This observation can complement the old observation by Dolgoshein et al. [13] that electrons can be extracted from some liquefied or solid noble elements. Our study with α -particles was concentrated on vapours compatible with the existence of the liquid phase. We have observed α tracks in mixtures of He + TEA + TMP or TMS. The ionization loss of α -particles in the gas phase at atmospheric pressure is of the same order as the energy loss of minimum-ionizing particles in liquids. For a liquid-argon detector, one has to find a gas phase that emits light. The candidates can be nitrogen, or methane—which is then also a sizeable fraction of the liquid phase. Our test with the wavelength shifters shows that we can visualize α tracks in the gas phase in mixtures of argon plus methane and nitrogen (Fig. 11).

REFERENCES

- [1] M. Suzuki, P. Strock, F. Sauli and G. Charpak, Nucl. Instrum. Methods **A254** (1987) 556.
- [2] M. Suzuki, A. Breskin, G. Charpak, E. Daubie, W. Dominik, J.P. Fabre, J. Gaudaen, F. Sauli, D. Sauvage, P. Strock and T. Zeludziejewicz, preprint CERN-EP/86-137 (1986), contributed to the 3rd Meeting on Advanced Detectors, Pisa, 1986.
- [3] G. Charpak, J.P. Fabre, F. Sauli, M. Suzuki and W. Dominik, Nucl. Instrum. Methods **258** (1987) 177.
- [4] R. Bouclier, G. Charpak, A. Cattai, G. Million, A. Peisert, J.C. Santiard and F. Sauli; G. Coutrakon, J.R. Hubbard, Ph. Mangeot, J. Mullie and J. Tichit; H. Glass, J. Kirz and R. McCarthy, Nucl. Instrum. Methods **205** (1983) 403.
- [5] G. Charpak and F. Sauli, Nucl. Instrum. Methods **225** (1984) 627.
- [6] M. Suzuki, CERN EP Internal Report 87-02 (1987).
- [7] A. Policarpo, Phys. Scr. **23** (1981) 539.
- [8] Y. Nakato, M. Ozaki and H. Tsubomura, J. Phys. Chem. **76** (1972) 2105.
- [9] J. Dupont, J.P. Fabre, P. Fonte, J. Gaudaen and M. Suzuki, internal report CERN/EF/INSTR/87-1 (1987).
- [10] M. Seya and F. Masuda, Science of Light **12** (1963) 9.
J. Berlman, Handbook of fluorescence spectra of aromatic molecules (Academic Press, Inc., New York, 1977).
- [11] G. Charpak, G. Demierre, K. Kahn, J.C. Santiard and F. Sauli, Nucl. Instrum. Methods **141** (1977) 449.
- [12] D. Anderson, G. Charpak, R. Holroyd and D. Lamb, FERMILAB-PUB-87/81 (1987).
- [13] B.A. Dolgoshein et al., Sov. J. Particles and Nucl. **4** (1973) 70.

Figure captions

- Fig. 1 Experimental set-up. The ionization electrons produced in a gaseous volume drift to a multiplying gap made of two parallel meshes set 9 mm apart. This set-up is the same as the one in Ref. [3], but the camera placed after the image intensifier has been replaced by a CCD camera. The chamber is closed by an Aclar window transparent to light with $\lambda < 200$ nm. PM: photomultiplier; HV: high-voltage supply; CP: charge-sensitive preamplifier; TD: timing discriminator; CC: coincidence circuit.
- Fig. 2 Example of minimum-ionizing tracks in the drift space represented in Fig. 1. The visible points are due to the avalanches from short-range δ -rays in the gas at atmospheric pressure: argon (91%) + CH₄ (7%) + TEA (2%).
- Fig. 3 Experimental set-up for studying the characteristics of the light emitted in a gaseous avalanche between the grids. Alpha-particles from ²⁴¹Am are stopped in the gas, and the ionization electrons are drifted to a multiplying gap. The light output is measured with a photomultiplier, type RCA 31000 M, and compared with the amount of charge collected on the electrodes. The spectrum can be analysed by a spectrophotometer, type ISA H.20UV, with a grating of 1200 grooves per millimetre. PM: photomultiplier; HV: high-voltage supply; CP: charge-sensitive preamplifier; LA: linear amplifier; PHA: pulse-height analyser.
- Fig. 4 Spectrum of light emission of avalanches in TMAE. Gas mixtures: argon (97%) + CH₄ (3%) + TMAE (0.4 Torr).
- Fig. 5 Emission of light by avalanches in a uniform field. Width of the amplification gap, $d = 1.5$ mm. Solid curves: collected charge; dashed curves: collected light. Gas mixtures: a) argon (98%) + TEA (2%); b) argon (97%) + CH₄ (3%) + TMAE (0.4 Torr). We observe the emission of light before any charge amplification sets in.
- Fig. 6 Relation between charge gain and light gain. Amplification gap width $d = 1.5$ mm: 1) Ar (95.5%) + N₂ (2.5%) + CH₄ (2%); 2) Ar (98%) + N₂ (2%); 3) Ar (98%) + TEA (2%); 4) Ar + TMAE (0.4 Torr). Amplification gap width $d = 1$ mm: 5) He (87%) + CH₄ (11%) + TEA (2%); 6) Ar (87%) + CH₄ (11%) + TEA (2%); 7) Ar (98%) + TEA (2%); 8) Ar (97%) + CH₄ (3%) + TMAE (0.4 Torr); 9) CH₄ + TMAE (0.4 Torr).
- Fig. 7 Light pulses from an X-ray source. The 5.9 keV X-rays from ⁵⁵Fe are producing light-pulses which are detected by a photomultiplier placed 100 cm from the chamber window. Gas mixture: argon (88%) + CH₄ (10%) + TEA (2%). Upper trace: collected light, lower trace: collected charge.
- Fig. 8 Alpha-particle tracks. The α 's from an ²⁴¹Am source are collimated along four axes at an angle of 90°. Gas mixtures: a) argon (88%) + CH₄ (10%) + TEA (2%); b) helium (92%) + CH₄ (6%) + TEA (2%) (the inset shows the collected charge).
- Fig. 9 A scattering event in helium. The α -particle scattered on a helium nucleus. The CCD gives the average ionization in each prong and the ionization loss along the initial tracks. Such a device would easily give a full image of the slow neutron capture on ³He, permitting great accuracy on the interaction point and total rejection of background.
- Fig. 10 A cosmic-ray event in a multistep TMAE chamber:
- Gas mixture: argon (75%) + CH₄ (25%) + TMAE (2.5 Torr).
 - Multistep operation: two parallel gaps of 4 mm separated by a 25 mm transfer gap.
 - Optical aperture: 1/4.5.

Fig. 11 An alpha track with wavelength shifter:

- Single step as in Fig. 1.
- Gas mixture: argon (95%) + CH₄ (2%) + N₂ (3%).
- Sodium salicylate layer against the last grid.
- Objective Leitz Noctilux 1/1:50 mm.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

a)

b)

Fig. 8

Fig. 9

Fig. 10

Fig. 11