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CERN, Geneva, Switzerland

(Presented by F. Sauli)

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Abstract: Photons emitted by avalanches in gases can be detected with an image intensifier coupled to a digitizing camera. We have investigated the emission properties of various gas mixtures in order to increase the light-yield. Several applications of the imaging chamber are illustrated: for high-granularity tracking of complex events and of electromagnetic and hadronic showers; for Cherenkov ring-imaging of charged particles and electromagnetic showers; and for use as a tracking device in a neutrino-tagging experiment.

1. Introduction

The imaging proportional chamber is a gaseous device in which the operating parameters are chosen to exploit the photons emitted by the electron avalanches at wavelengths close to or in the visible range [1-6]. Electrons produced in the gas by ionization are drifted towards a region of high electric field, where charge multiplication occurs accompanied by photon emission; the plane of detection is viewed by an image intensifier, and the optical information is recorded using a camera coupled to a video digitizer. As detectors, we have used several structures combining preamplification, gating, and amplification elements based on the multistep proportional chamber [7]. Using a commercially available solid-state charge-coupled device (CCD) camera as the recorder, one can obtain granularities in the megapixel region—which would be unthinkable using electronic detectors. Whilst the readout rate is rather low (50 Hz is standard, 1 kHz is probably a practical limit for today's technology), a built-in delay due to the drift time in the gas, which can be of several microseconds, allows selective readout or gating of the information; the image intensifier itself can be gated with a fast (down to few nanoseconds wide) pulse in order to reduce the sensitive time and therefore the noise.

The main outcome of the systematic search for light-emission intensity and spectral range in electronic avalanches for various gas mixtures, described in the references given above, is that the addition of low-ionization-potential vapours, such as triethylamine (TEA) and tetrakis(dimethylamine)ethylene (TMAE), to moderately quenched mixtures of rare and organic gases, results in the copious emission of fluorescent photons, increasing in absolute quantity with the amount of additive up to a saturation point. Water has also been found to be a very effective scintillator under avalanche conditions. The highest light-yields are obtained using uniform-field multiplying structures, as compared with thin-wire chambers—an obvious practical advantage. The amount of light emitted is proportional to the primary energy loss, as is also the case for the measured charge. The results of the study have opened the way to several applications, both in particle physics and in other fields; some of these will be described below.

2. Experimental Apparatus

In all applications of the imaging chamber to be described, we have used, as gas fillings, various mixtures containing TEA, which emits photons under avalanche conditions in a broad peak centred around 280 nm [3], or TMAE, with an emission peaked at 480 nm [6, 8, 9]. We have systematically investigated the scintillation properties and light-yield of the mixtures as a function of concentration and in various geometries of parallel-plate avalanche chambers (PPACs) and multiwire proportional chambers (MWPCs) [5, 8]: the results can be summarized as follows. The highest relative light-yield (ratio of photons to charge detected) can be attained in the uniform amplification field of a PPAC, indicating a preference for large multiplication gaps; the relative light-yield is maximum at moderate charge gains, but of course the absolute number of emitted photons increases with the gain. The light emission efficiency at a given charge

Fig. 1 Light-yield from avalanches in a uniform field, relative to charge gain (kept constant at around 100), as a function of the partial pressure of TEA in argon (1) and xenon (2) at one atmosphere.

Fig. 2 Same as in Fig. 1, for TMAE in argon (1), neon (2), and helium(3) at atmospheric pressures.

gain increases with the amount of the vapour in the noble gas, at atmospheric pressure, until saturation is reached at partial pressures around 2-3 Torr (Figs. 1 and 2) [10]; the addition of a quenching gas to the mixture, such as methane or ethane, decreases the light-yield to some extent but improves the stability of operation of the detectors.

The use of TMAE is obviously convenient because of its emission in the visible range, but on the other hand its low vapour pressure at room temperature (0.4 Torr) results in a rather poor scintillation efficiency and in a limited charge gain (because of photon feedback problems), unless one accepts the inconvenience of operating the detectors at high temperature. The high vapour pressure of TEA (52 Torr at 20 °C) makes it possible to attain large light-yields, but this advantage is attenuated by the necessity of using an imaging system operating in the close ultraviolet, a region where the choice of optical components for the image intensifier is rather restricted.

The use of a wavelength shifter placed close to the light-emitting gap can solve the dilemma, but possibly with a slight decrease in the localization accuracy, owing to diffusion. Notice, in this respect, the fundamental advantage of using a parallel-plate amplification (where most of the light is emitted close to the last electrode) instead of a multiwire chamber. The results obtained with a thin layer of sodium salicylate deposited on the inside surface of the Mylar window of the

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detector have been already discussed [8]. Recently, even better results have been obtained using a specially manufactured thin-foil plastic wavelength shifter, developed at our request [11]; with an excitation spectrum between 260 and 340 nm, and a fluorescence spectrum peaked at 425 nm, it allows a very efficient shift of the TEA emission into the visible range. The intensity of the light emission measured when using the wavelength shifter was found to be about one half of that obtained (at shorter wavelengths) without the foil; this loss is largely compensated by the possibility of working with light in the visible range, with commercially available objectives that have larger apertures.

An example of a multistep chamber, used for the measurements described in Section 5 and, with some modifications, for the other applications, is shown in Fig. 3. A succession of electrodes at suitable

Fig. 3 Schematics of an imaging multistep chamber. The large gap between the preamplification and the gating electrode is used to provide the delay exploited in the neutrino-tagging application.

potentials, realized with crossed wire grids or, as in the case of the gating electrode, with a mesh of thick parallel wires, define several regions in the gas volume. First, a conversion region where charged particles or photons release ion pairs by ionization; then, a region of high field where electrons are preamplified in a parallel-plate avalanche multiplication, followed by a moderate-field transfer region to the last gap, where a second step of avalanche multiplication occurs. A gating electrode, where an appropriate potential applied between pairs of wires can stop or transmit the drifting electrons, is used for selective detection of ionization. The drift-time in the transfer gap, which can be increased to several microseconds, allows a comfortable decision-making time for the selection; both the charge and the light emitted in the last amplification gap can be recorded. In gas mixtures containing photosensitive vapours, this structure makes it possible to reach the high charge gains that are necessary for detecting single electrons, as required, for example, in Cherenkov ring-imaging [12–15].

Several models of image intensifiers have been used during this search; they are described in the quoted references. The one employed for the imaging of visible light (emitted directly by TMAE, or by TEA when using the above-mentioned thin-foil wavelength shifter) is shown

schematically in Fig. 4. A suitable optical element (an objective or a simple lens) focuses the image, generated by the avalanches in the detector, onto the photocathode surface of the first element of the intensifier, a multichannel-plate light amplifier (Delft Elektronische Producten type DEP XX 1450M). This element has an 18 mm active diameter with an S20 photocathode and a P47 phosphor screen; it can operate in either a continuous or a gated mode with a minimum gate opening, for full efficiency, of about 100 ns (limited by the high-voltage pulser). Both the photocathode and the fluorescent screen are deposited on thin fibre-optics windows; the photon gain of the first stage is about 1000 at nominal operating voltage. The output of the first stage is coupled to the fibre-optics window of the second electrostatic image intensifier-reducer (type DEP XX 1490), demagnifying the image from a diameter of 18 mm to 7 mm, which matches the size of the solid-state CCD camera. The nominal photon gain of the second element is around 7 at the operating voltage; it has an S20 photocathode and a P46 fast phosphor screen, with a decay-time of 100 ns, allowing efficient coupling to the CCD. For the time being, we are using a moderate-resolution camera (Thomson TH 7852 FO, with 144×208 pixels); the use of a higher-resolution CCD is foreseen. Images are digitized by a commercial frame-grabber with an 8-bit resolution over 512×512 pixels, and read out with a personal computer.

3. Imaging of Electromagnetic and Hadronic Showers

The high granularity of the imaging chamber and its capability to provide good information about the energy loss by the measurement of the scintillation yield, makes it very suitable for the detection of showers in a sampling calorimeter. Early results with a small prototype detector of this kind were presented in Ref. [4]. Originally developed for the detection of hard X-rays in positron cameras [16], the high-density proportional chamber (HPC) is used extensively in large experiments for the detection of electromagnetic showers [17, 18]. It consists of a drift and conversion region, where a succession of thick metal electrodes, insulated from each other and at a suitable field gradient, generates the shower. Gas channels cut through the converter allow the ionization electrons, produced by the charged component in the shower, to drift towards a detection element—a MWPC in the conventional design. We have modified a prototype HPC*, replacing the thin-wire chamber with a pair of meshes defining a parallel-plate multiplication region; in order to reject noise and unwanted events, the cathode of the amplifying gap was pulsed so as to reach the nominal operating voltage during the charge collection time only. Note that the possibility of activating the detector for a short time, pulsing a special gating electrode or a cathode without problems of electronic pick-up of the noise, is one of the advantages of the optical readout.

The active size of the detector was $54 \times 54 \text{ cm}^2$, with a conversion region 27 cm thick and presenting 10.5 radiation lengths to the shower development. As a gas filling, we used a mixture of argon (88%) + methane (10%) + TEA (2%); the short wavelengths emitted by the scintillation of TEA are shifted into the visible region by the thin-foil wavelength shifter described in the previous section, which is placed on the last electrode in the chamber. A double Mylar window with a gas flow in the interface was used for gas tightness. The detector was installed in an unseparated beam of charged particles at CERN, and a standard system of threshold Cherenkov counters allowed the electron component to be tagged.

Figures 5a–c show, respectively, the recorded images for an electromagnetic shower and for a hadronic interaction, both at 8 GeV/c, and for a non-interacting minimum-ionizing particle; colour coding of the light intensity—not apparent in the monochrome reproduction—shows beautifully the energy loss distribution within the showers. Whilst we cannot yet provide values for the energy resolution (the analysis of data is in progress), the high granularity of the visual detection is apparent from the pictures. For example, it enables a hadronic interaction to be clearly distinguished from an electromagnetic one; multiple showers can also be identified, with a resolution of probably a few centimetres.

*) Kindly provided by the HPC group in DELPHI at CERN.

Fig. 4 Schematics of the image intensifier and video digitizer used to record the images in the detector.

Fig. 5 Images recorded with the high-density detector, for
a) an electromagnetic shower,
b) a hadronic interaction, and
c) a minimum-ionizing particle.

4. Cherenkov Ring-Imaging

The high granularity of the imaging chamber, and the fact that it operates with a photosensitive vapour to enhance the scintillation efficiency, makes it an ideal detector of photons emitted by Cherenkov effect in a radiator and focused in a ring pattern, and especially in the case of high multiplicities (due to the multihit limitations of electronic detectors). The results obtained with a prototype Cherenkov ring imager based on a low-pressure multistep imaging chamber have already been reported [19, 20].

Some time ago, it was suggested that the direction of high-energy γ -rays could be determined by detecting the pattern of Cherenkov photons emitted by the electrons produced in showers developing in dense materials [21]. The method relies on the fact that, at the beginning of the shower development, the direction of the electrons is strongly correlated with the direction of the γ -ray initiating the shower. Using a solid or liquid radiator with a spherical mirror at the rear, one obtains a ring-like image generated by the photons reflected on the image plane; a detector with a photosensitive-vapour filling can then be used to record the pattern. The practical problem is that one expects several hundred or more photons in the ring, a multiplicity difficult to cope with using electronic detectors; the imaging chamber is therefore the obvious choice.

The multistep avalanche chamber used for the measurement is shown schematically in Fig. 6 [22]. It has an active area of $20 \times 20 \text{ cm}^2$ and an input CaF_2 window, transparent to photons of a wavelength above 130 nm. Operated with a mixture of helium and ethane at atmospheric pressure, and with saturated TMAE vapour, it allows charge gains close to 10^6 to be reached in the two-step structure. Helium has been preferred to argon because of the low specific ionization produced by charged particles—around six ion pairs per minimum-ionizing track in the 7 mm thick conversion gap (a source of

Fig. 6 The imaging chamber for the detection of Cherenkov rings generated in the solid or liquid radiator by charged particles or electromagnetic showers.

background at high rates). The exit window for the imaging of the light emitted in the avalanches is made of common Pyrex. In order to improve the light-yield and the quantum efficiency, the detector was operated at temperatures between 35°C and 45°C , corresponding to TMAE concentrations of about 0.2% and 0.3%, respectively. Since a gating facility was not included in the design of the chamber, it was

Fig. 7 Distribution of a) the spot size and b) the centre of gravity for the imaging of single photoelectrons. In (b), the distance between two collimated beams is 1.9 mm.

implemented by applying a short (1 μ s) high-voltage pulse to the last cathode, thus adding 400 V to the already applied voltage. The timing of the pulse was chosen so as to increase the field just before the preamplified cloud of electrons penetrated the last gap, and the overall potential did not exceed the proportional amplification region.

We have measured the single-photon position resolution and avalanche size, using as the photon source a pulsed hydrogen lamp, collimated and attenuated to make sure that single photoelectrons were produced in the chamber. As shown in Figs. 7a,b [22], the avalanche size distribution, as recorded through the image intensifier and the CCD camera, has an average FWHM of 3 mm, and the localization accuracy, computed taking the centroid of the spot intensity distribution, is of about 220 μ m r.m.s. (the two peaks in Fig. 7b correspond to two positions of the collimated photon source, 1.9 mm apart).

The detector was installed in an unseparated beam of charged particles; electrons in the beam could be tagged by a conventional threshold Cherenkov counter. As the radiator, we first used a BaF₂ crystal, specially cut with a spherical reflective shape at the far end; the results were, however, rather confusing owing to a large contribution of direct scintillation in the crystal adding a conspicuous background to the expected ring pattern. Much better results were obtained using a radiator of purified liquid Freon (C₆F₁₄). A spherical mirror facing the chamber is positioned so as to focus, on the window, the photons emitted in the radiator; the radiator itself is about 52 mm thick. Figure 8a shows a typical Cherenkov ring generated by 10 GeV/c pions crossing the radiator; the average number of spots in the ring is about 20, which is what one would expect from the known characteristics of the detector and of the radiator.

Selecting electrons at 10 GeV/c, we detected Cherenkov rings corresponding to electromagnetic showers. Because of the modest thickness of the radiator (0.3 radiation lengths, including the window), we installed a lead-glass slab, 1 cm thick (1 radiation length) in front of the chamber in order to enhance the development of the shower. As the slab is transparent to visible light, it does not perturb the imaging properties of the detector. Figure 8b shows an example of the image obtained for a developing electromagnetic shower.

Fig. 8 Cherenkov ring generated in a 52 mm thick liquid-Freon radiator a) by fast charged pions and b) by a developing electromagnetic shower.

The data analysis (not yet completed) should provide information on the pattern recognition properties, the efficiency, and the angular resolution of the device.

5. The Imaging Chamber for Neutrino Tagging

We have investigated the possibility of using the imaging chamber with a rather thick transfer space to provide a selective detection of tracks after a very long delay—several microseconds or so—such as is required for a proposed tagged-neutrino experiment [23]. The basic idea is to install, in the decay region of the extracted beam, a large-area position detector that is capable of withstanding a very high particle rate (up to 10^6 cm⁻²) and measuring the trajectory of the decay electron or muon that accompanies the production of neutrinos. As the interaction rate in the neutrino detector is very small, one has to record selected events in the decay region; however, the physical distance between the two parts of the apparatus is very large (several hundred metres), thus requiring a very long memory or delay for the events, without loss of information. Although possible, an electronic, dead-time-free delay of several microseconds for tens of thousands of signals produced by a MWPC system does not seem very attractive. With its built-in gaseous delay, a multistep chamber can provide the answer.

Fig. 9 Spot-size distribution (a) and localization accuracy in projection (b) for fast particles detected with the imaging multistep chamber with $2 \mu\text{s}$ delay in the gap between the preamplification and the main amplification elements.

The operation of multistep chambers with a fast gating was already demonstrated some time ago [24]; in that case, after a drift length in the transfer region (between preamplification and the gate) of 10 mm, corresponding to a delay of about 250 ns, the full efficiency for the detection of minimum-ionizing particles was obtained with a 30 ns wide pulse applied to the gating electrode. The multistep imaging chamber used in this study was described previously (see Fig. 3); segments of ionization trail 3 mm long, generated in the conversion region, are preamplified by a factor of about 500 (including the transfer efficiency). An 11 cm thick transfer region allows the preamplified cloud of electrons to be delayed by about $2 \mu\text{s}$; the actual delay can be finely tuned by adjusting the electric field and therefore the drift velocity. Because of the length of the detected track segment (3 mm) and of the long drift distance with the resulting diffusion, the minimum gate-width for full efficiency is up to about 50 ns. Selected tracks, in coincidence with the gate pulse, are then fully amplified and detected by the image intensifier and digitizer system.

The detector was installed in a high-energy charged-particle beam, in line with a pair of silicon microstrip detectors^{*)} that made it possible to measure the vertical coordinate of each track with very good precision. Data from both the silicon strips and the video digitizer were recorded on tape.

A preliminary analysis of the data shows that after the $2 \mu\text{s}$ delay, the average spot-size distribution has a most probable value of 1.2 mm (Fig. 9a), whilst the vertical localization accuracy (computed as the difference between the centre of gravity of the spot and the coordinate given by the silicon strips) has a distribution with $400 \mu\text{m}$ r.m.s. (Fig. 9b). Work is in progress to study the operating characteristics and the resolution power of the device, particularly in a high-intensity particle flux such as the one foreseen for a neutrino-tagging detector.

References

- [1] R.S. Gilmore et al., Nucl. Instrum. Methods **206**, 189, 1983.
- [2] D.M. Potter, Nucl. Instrum. Methods **228**, 56, 1984.
- [3] M. Suzuki, P. Strock, F. Sauli and G. Charpak, Nucl. Instrum. Methods **A254**, 556, 1987.
- [4] G. Charpak et al., Nucl. Instrum. Methods **A258**, 177, 1987.
- [5] M. Suzuki et al., Nucl. Instrum. Methods **A263**, 237, 1988.
- [6] G. Charpak et al., IEEE Trans. Nucl. Sci. **NS-35**, 483, 1988.
- [7] G. Charpak and F. Sauli, Phys. Lett. **78B**, 523, 1978.
- [8] G. Charpak et al., Nucl. Instrum. Methods **A269**, 142, 1988.
- [9] D. Sauvage, A. Breskin and R. Chechik, Weizmann Inst. preprint WIS-88/8 (1988), submitted to Nucl. Instrum. Methods.
- [10] G. Charpak, W. Dominik, V. Peskov and F. Sauli, Investigation of light emission of noble gases with TEA, TMAE, and H_2O vapours in a PPAC at atmospheric pressure, to be published.
- [11] M. Bourdinaud, private communication.
- [12] R. Bouclier et al., Nucl. Instrum. Methods **205**, 403, 1983.
- [13] F. Sauli and G. Charpak, IEEE Trans. Nucl. Sci. **NS-32**, 663, 1985.
- [14] F. Sauli, Nucl. Instrum. Methods **A248**, 143, 1986.
- [15] A. Breskin and R. Chechick, Nucl. Instrum. Methods **A252**, 488, 1986.
- [16] A. Jeavons, G. Charpak and R. Stubbs, Nucl. Instrum. Methods **124**, 591, 1975.
- [17] H. Fisher and O. Ullaland, IEEE Trans. Nucl. Sci. **NS-27**, 38, 1980.
- [18] M. Berggren et al., Nucl. Instrum. Methods **225**, 477, 1984.
- [19] A. Breskin et al., Weizmann Inst. preprint WIS-87/68 (1987), to be published in Nucl. Instrum. Methods.
- [20] A. Breskin et al., IEEE Trans. Nucl. Sci. **NS-35**, 404, 1988.
- [21] Y. Giomataris and G. Charpak, preprint CERN-EP/88-94 (1988), subm. to the 20th Int. Cosmic Ray Conf., Moscow, 1987.
- [22] Y. Giomataris et al., preprint CERN-EP/88-96 (1988), submitted to Nucl. Instrum. Methods.
- [23] F. Vannucci et al., private communication.
- [24] A. Breskin et al., Nucl. Instrum. Methods **178**, 11, 1980.

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