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ABSTRACT

Substantial progress is observed in the detection and localization of photons with gaseous detectors:

- Single-step or multistep chambers with photo-ionizable gases allow the imaging of VUV photons over surfaces of the order of 1 m^2 with localization accuracies of a few hundred microns.
- The combination of scintillation proportional counters with wire chambers permits resolution energies of the order of 8% FWHM at 6 keV, with localization accuracies of the order of 1 mm. This technique is promising, up to energies of the order of 100 keV.
- The use of gas mixtures producing light pulses of less than 2 ns duration in electron avalanches is a further step in the energy resolution of soft X-ray detection, by allowing the counting of ionization electrons. Plastic wavelength shifters with equivalent timing properties permit an extension of this technique to large-surface structures.

INTRODUCTION

The interest of this symposium is focused on the detection of photons over a wide range of energies.

Every domain of energy corresponds generally to a different approach to the detection problem.

The adaptation of the detector to the very special conditions of spatial flights imposes also severe restrictions on the choice of a solution. My ignorance in this field will preserve me from making any relevant statement on this aspect of the problem.

In my talk I will skip those topics which correspond to some well-established techniques.

Scintillation counters is one example of those. It is worth mentioning, however, that new scintillators are becoming available, whose commercial development was boosted by the importance of their applications in radioisotopes imaging, or X-ray scanners. Let me just mention a few of them which are attracting great attention in high-energy physics: bismuth germanate (density 7.13, radiation length 1.12 cm), which is being considered as a valid candidate for massive photon calorimeters, and barium fluoride; with the latter, a group at Grenoble has reached time resolutions of 120 ps (FWHM) with annihilation photons in coincidence. ¹/ This can become interesting for time-of-flight measurements over a short basis.

The use of solid-state detectors is the second example of a rather stable technique. Their limitation in spatial research is sometimes their small maximum size (1 litre) compared to scintillators, and the drawback of permanent deep cooling during measurements. There is still hope of bringing to an operational step some promising crystals not requiring cooling, such as HgI_2 or CdTe , and progress on these is announced at almost every instrumentation conference.

Not being an expert on these detectors, I will limit myself to the field of gaseous detectors, where a steady evolution is observed due to the diversified needs in high-energy physics and to the work and inventions of many groups. The stimulation is coming from the search for

¹ R. Allemand, Laboratoire d'électronique et techniques de l'informatique, Grenoble, France, private communication.

higher spatial accuracies, better particle identification, more accurate energy measurements in calorimetry, etc. I will limit myself to those topics related to the detection of photons, and refer the reader to the latest conferences on instrumentation in high-energy physics for a broader view on the innovations in this field.

THE STATE OF THE ART IN GASEOUS DETECTORS

Progress in the understanding of the mechanisms of avalanche formation and pulse induction has led to a noticeable improvement in the quality of the information obtained from wire chambers. In addition to getting the coordinates of the avalanches along a wire, it is generally possible to obtain with accuracy the azimuthal angle of an avalanche [1].

This has transformed the wire chamber -- at least for low-energy radiations giving rise to an avalanche localized on a single wire -- into an imaging detector with a continuous response in the two coordinates, parallel and perpendicular to the wires. For drift chambers this observation permits an easy solution of the right-left ambiguity.

The accuracy obtained from the decoding of the pulses induced on appropriate electrodes is usually limited only by the spatial extension of the ionization electron swarm amplified near the wires. A drastic reduction of this extension, due to δ -rays of finite range or due to diffusion, has been obtained by increased pressure. Even at moderate pressures, such as 5 atm, accuracies of 20 μm are obtained in drift chambers [2], and some authors claim particle separation of the order of a few hundred microns. Research on high-pressure gaseous detectors above 100 atm is being actively pursued in several high-energy groups.

A diversification of the amplifying structures is observed in connection with the introduction of the multistep chambers. These rely on a first stage of amplification between parallel grids, and a subsequent transfer to drift spaces or other multiplicative structures. It is interesting to note that this research, first aimed at reaching high counting rates by intermediate gating of the electrons from the preamplified gap [3], has led to unexpected developments. It showed that parallel-plate structures, known well from experience in low-energy nuclear physics to work properly at low gains and at low pressures, are sometimes quite competitive with wire chambers for moderate gains at atmospheric pressure [3,4].

Some simultaneous research on these structures, not related to multistep chambers, has also shown encouraging results in this field for low-energy X-ray imaging [5].

However, it is our experience that a multistep structure, where a parallel gap is combined with a wire chamber, permits easier detection of single electrons, with a large gain reaching 5×10^7 , with a localization accuracy of $\sigma = 300 \mu\text{m}$ over large surfaces.

Finally, besides the progress in the readout method, in the diversification of the structures, a better insight into the gaseous processes has led to spectacular developments in the art of controlling and using the various VUV or visible photons absorbed or emitted by the molecules of the gas fillings [4]. New generations of VUV or X-ray imaging counters are connected with these last developments, and progress in detecting and imaging high-energy γ -rays in the MeV region is in view.

THE APPLICATION OF GASEOUS DETECTORS TO PHOTON IMAGING

We will now see, in the different ranges of energy, how the above-mentioned progress in structures, readout, and gas control is leading to an evolution of the available instrumentation.

Detection of Single VUV Photons

In high-energy physics the incentive for the detection of VUV photons is coming from the importance of the imaging of Čerenkov light for the identification of relativistic particles. The small quantity of available photons and the saturation of the Čerenkov angle with increasing energies make it necessary to have detectors with high efficiency and high accuracy.

The first step in this field was the suggestion [6] to use an appropriate combination, in multiwire chambers, of vapours with a low ionization potential, with windows having a cut-off energy well above these ionization potentials.

The importance of this problem for many high-energy physics experiments had led to several developments, from which I will extract the following most salient features.

Figure 1 shows the quantum efficiency of some vapours that are of practical interest, and the transmission of some windows.

Practically, triethylamine (TEA) and tetrakis(dimethylamine)ethylene (TMAE) are used. The first one, with an ionization potential of 7.5 eV, requires CaF_2 windows. The second, with an ionization potential of 5.4 eV, is compatible with quartz windows.

Fig. 1 a) Quantum efficiency of various vapours, and transparency of various windows. TMAE and TEA: see text. b) Absorption of some vapours.

I do not want to enter into the details which might lead a group to like one vapour more than the other — details which may be of major practical importance for a given experiment. I only want to mention that it is possible to obtain a good amplification, permitting the detection of single electrons in one stage of amplification with wire chambers filled with pure methane and TMAE [7], or with multistep counters [8-10]. In this case we have experimented with imaging Čerenkov counters at CERN and Fermilab, and separated pions from kaons up to 200 GeV/c [11]. The accuracy we reached, using the computed centroid method, was 400 μm for a $20 \times 20 \text{ cm}^2$ chamber, and we are at present conducting an experiment at Fermilab on a chamber with the same characteristics but with a surface of 0.4 m^2 . Figure 2 illustrates the imaging quality of this detector for VUV photons.

In the course of this development we have studied multistep chambers where the second stage is a spark chamber viewed by vidicon cameras of great simplicity [10], and with targets made of layers of gases or of thin crystals which were precious for separating particles or measuring energies in the GeV range.

Fig. 2 Images of Čerenkov light in a multistep avalanche chamber (from Ref. 10). First step: parallel gap. Second step: MWPC. Gas mixture: He + CH_4 + TEA. Total gain 5×10^7 . a) Single event. b) 200 events. Čerenkov ring radius = 6.8 cm. Beam of 200 GeV/c pions.

Imaging of Low- and Medium-Energy X-Rays using the Scintillation Light

A development which is now familiar in space research is the gas scintillation proportional counter (GSPC), where VUV photons are produced by ionization electrons drifting in pure noble gases under the influence of electric fields. These VUV photons are usually converted to visible light and detected in photomultipliers [12].

Imaging detectors using the same principle as that of the Auger camera were first introduced by Nguyen et al. [13], with the aim of imaging X-rays up to 100 keV for medical applications. Resolutions close to 3% FWHM were reached at 60 keV with localization accuracies of 3 mm (FWHM).

A similar approach has been successfully attempted by a space research group [14].

With the advent of gaseous detectors sensitive to VUV, it was quite a natural step, proposed first by Policarpo [15], to replace the photomultipliers by photosensitive wire chambers (Figure 3a). This was successfully demonstrated by several groups.

Whilst we did this at CERN with TEA vapour [16], it was the occasion for Anderson to introduce the TMAE into this game [17]. The imaging detector developed at Columbia University in the group of Prof. Novick is a successful application of this principle: accuracies of 1 mm are claimed and the energy resolution can reach 7.8% FWHM for the 5-9 keV X-rays (Figure 3b), like the best scintillation proportional counters using photomultipliers.

It is clear that with high-pressure xenon chambers of this type we are going to have a combination of good energy resolution and spatial resolution which is barely matched by any other detector up to energies close to 100 keV. The limitations will come from the physical processes giving rise to spatial extensions of the ionization clouds: range of the electrons, escape peaks, diffusion ...

a)

b)

Fig. 3 Photo-ionization proportional scintillation counter (PIPS). a) Schematic view. The X-rays are absorbed in a pure noble gas. The drifting ionization electrons produce VUV light in a scintillation gap. The VUV photons traverse a window and are detected and localized in a wire chamber with a photo-ionizable vapour (TEA, TMAE, acetone, etc.). b) Energy resolution: 5.9 keV and 6.4 keV from a ^{55}Fe source; 7.8% FWHM (D. Anderson). Gas filling: 400 Torr Ar + 100 Torr isobutane + 0.3 Torr TMAE. CaF_2 window. Gas scintillation proportional counter: 760 Torr xenon.

Imaging of Low-Energy Photons by Electron Counting

The ultimate accuracy that can be obtained with a gaseous detector absorbing a photon can be reached if one finds access to the exact number of electron pairs liberated in the gas. The accuracy is then a function of the Fano factor only, which is varying with the gas, but all the fluctuations introduced by the amplification processes are then eliminated.

A rough estimate shows that an accuracy of 4% FWHM could be reached at 5.9 keV. To my knowledge, several groups are engaged in this type of research for quite different physics goals.

A major step forward in this approach was made by Siegmund et al. [18]. They observed that by detecting the flashes of visible light produced in avalanches it was possible to find an appropriate gas where the duration of the pulses is only 2 ns, i.e. about 10 times shorter than those obtained by using the pulses induced by the motion of the electrons or ions. They first drift the ionization electrons in a gas at low fields in order to separate the electrons, and then produce an electron avalanche, with a gain below 10^6 , in a 3 mm gap with a gas filling made of Ar + N_2 + CO_2 or CH_4 .

The role of N_2 , as is well known from previous work on the light emission in proportional counters, is to convert the excitation energy of Ar into the excited level of N_2 , leading to emission in the visible region. Figure 4, from ref. [19], shows the spectrum of a mixture of Ar with only 0.1% of N_2 . The role of CO_2 or CH_4 is multifold. They quench the excited states of argon and control the duration of the light pulses, and they govern the drift velocity or the diffusion.

Fig. 4 Emission spectrum of an Ar (99.9%) + N_2 (0.1%) mixture (Ref. 18).

Fig. 5 Traces of the light pulses for a C K X-ray event. The individual peaks correspond to avalanches initiated by single electrons. The gas used was Ar + CH_4 (4%) + CO_2 (5%) + N_2 (7.5%) with a drift-region field strength of $\sim 10 \text{ V cm}^{-1}$ and a gas gain of 10^5 (from Ref. 17).

The results are spectacular, as seen in Figure 5, and this gain of 10 in time resolution permits a relatively easy counting of the separated electrons.

Siegmund et al. have applied this method successfully for the C K-line of 283 eV and the gain in energy resolution is satisfactory.

However, the extension of this method to higher energies is more difficult as more electrons have to be counted.

We have made a development, in our group at CERN [20], which may lead to an easier extension towards higher energies.

We have found a plastic wavelength-shifter with the characteristics summarized in Table 1, and which was developed as a wavelength-shifter and light-guide for scintillators.

TABLE 1 Properties of Altustipe WLS 390 A *) converter

Peak absorption at 400 nm, absorption length 2.5 mm, efficiency 80-90%

Peak emission at 433 nm, attenuation length 2.5 m

Fluorescent light rise-time: $\leq 1 \text{ ns}$

decay-time: $\leq 2 \text{ ns}$

Refractive index: 1.520

Basis: Polymethyl methacrylate

*) Commercialized by Altulor, Tour Gan, Cedex 13, 92892, Clichy, France.

The decay time of the light excited in this shifter being also of about 2 ns, we observed that it is easy to efficiently detect the pulses from single electrons giving rise to avalanches around 10 μ m wires in a multiwire chamber (Figure 6). This allows a considerable improvement in the practical structure of detectors exploiting the fast pulses of light produced by the atoms excited by the avalanches near a wire. For instance, it is possible to exploit also the lateral diffusion of the electrons and have narrow strips of wavelength-shifters viewing different wires or different adjacent parts of a parallel-grid amplifying structure, or a wire chamber, with a multiplicity of photomultipliers detecting the pulses independently.

This method offers a practical way of exploiting the scintillation drift chamber introduced some time ago and which showed spectacular properties in high-rate counting, making it possible to reach 10^6 counts/mm²·s without losses. Owing to the many applications in high-energy physics, this method will certainly be developed rapidly.

Fig. 6 Light pulses from single electrons after conversion in the plastic wave shifter. The electrons are produced by absorbing 1.5 keV X-rays separating them by diffusion, producing avalanches near a wire, converting the light on a sheet of WLS 390 Å and viewing the edge with an XP 2020 photomultiplier. The scale is 2 ns/major div. and the gas mixture used is Ar + N₂ + CH₄.

A feature that demonstrated beautifully the advantages of visible light detection over the detection of pulses induced by the motion of the ions is illustrated in Figure 7 by the comparison of pulses produced by 1.5 keV X-rays and 5.9 keV X-rays, after 1 cm of drift, in a gas where the conditions are chosen to minimize the diffusion and the separation of the initial ionization electrons. The pulses from the 1.5 keV photons are systematically narrower and of different aspect than those from 5.9 keV photons. The difference reflects the difference in physical structure. In the first case we have a photoelectron of at most 1.5 keV. In the second case we have two electrons of about 3 keV: the photoelectron from the K-shell of Ar and the Auger electron.

The pulses from minimum ionizing electrons also show perfectly the structure of the primary ionization [18,20].

Imaging of γ -rays

The developments mentioned so far were all limited to energies below 100 keV. However, there are prospects of progress at higher energies.

Let me mention the efforts that are being made to use drift spaces with solid converters [21,22] in order to increase the efficiency for γ -rays of typically 0.5 MeV. The aim is to detect annihilation radiation in positron imaging for medical purposes. Efficiencies of the order of 10% are being reached, but the absence of energy resolution can be a limiting factor for some experiments. It is compensated in the above-mentioned application by an excellent position resolution of the order of one millimetre. A development which may lead to a step forward is the attempt to combine scintillation crystals with imaging photoionization multiwire chambers.

Fig. 7 Light pulses from 1.5 keV and 5.9 keV X-rays. Traces of light pulses from a wire chamber; 4 mm wire spacing, 10 μ m wire diameter, 1 cm gap. Ar + CO₂ + N₂ filling (73 + 17 + 10)%. Operating voltage: 3000 V. Wavelength-shifter Altustipe WLS 390 A, viewed at the edge by an XP 2020 photomultiplier; 10 ns/main division.

So far, Anderson [17] has succeeded in obtaining an efficiency of 3% with barium fluoride crystals. There is only a tiny overlap between the emission spectrum of this crystal and the sensitivity of TMAE. A little progress with respect to TMAE could have spectacular results for the efficiency. On the other hand, it is possible that although the efficiency is hopelessly small at 0.5 MeV, it may be sufficient for domains of energy in the 10 MeV range where no very practical high-accuracy imaging cameras exist. It should also be mentioned that at higher energies the drift spaces with solid converters show some energy resolution and are the subject of active research for high-energy electromagnetic calorimeters [23].

CONCLUSIONS

If we exclude some hypothetical possible progress that could open up a prospect of high-accuracy imaging and energy measurement of photons in the MeV range, we may say that up to 100 keV, and starting at the level of VUV photons, these last years have seen quite new possibilities for photon imaging cameras, with dramatic progress in efficiency, in position, or in spatial resolution. A wide field of research is still open and awaiting further exploration.

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