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EMISSION AND ABSORPTION OF PHOTONS IN GASEOUS DETECTORS

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ABSTRACT

In this paper some of the progresses due to a better understanding of the emission and absorption of photons in gaseous detectors are discussed. The possibility of imaging photons from 4 to 10 eV offers many possible applications, discussed in this paper, for X-ray imaging, high-energy calorimetry, particle identification, etc.

While ultraviolet photons have been known for a long time to play a major role in the mechanism of the Geiger counter, more recent developments are due to a deeper understanding and control of emission and absorption of photons in gaseous detectors. This is illustrated by the operation of wire chambers in the limited Geiger or streamer mode, gas scintillation proportional counters, proportional photo-ionization scintillation counters, multistep avalanche chambers, and various types of detectors for photon imaging.

At a symposium held in conjunction with the commemoration of the 100th anniversary of the birth of H. Geiger, I thought it appropriate to discuss the photon emission or absorption in gaseous detectors, and this for several reasons. It so happens that my group has been actively engaged, at CERN, in some developments based on the exploitation of these phenomena¹⁻³). Also my personal interest in particle detectors grew from the construction of Geiger counters in my first steps as an experimentalist: looking in the dark at the wires illuminated by the excited ion sheath in Geiger counters, I started the study of light pulses in proportional counters⁴).

At the present time many groups have invented new devices based on the understanding or control of the various electromagnetic radiation phenomena connected with the collisions of electrons in gases and I would like, in this contribution, to review briefly some of these advances in detector techniques.

1. THE EMISSION OF PHOTONS IN GASEOUS IONIZATION DETECTORS

When electrons are drifting in gases under the influence of electric fields they can experience a variety of inelastic collisions, leading to the emission of light. In many cases, with mixtures commonly chosen in gaseous detectors for some empirical reasons, a precise prediction is impossible because of the scarcity of experimental data. The situation is understood in noble gases and in noble gas mixtures, and data are available for some mixtures of noble gases with quenching agents such as N₂, CH₄,

or CO_2 . Nevertheless, some simple guide-lines have proved to be effective in controlling the operation of counters even with complicated mixtures.

1.1 Noble gases

Various states contribute to the emission of photons when the atoms of noble gases are excited by electrons accelerated by electric fields. The spectra are strongly dependent on the gas pressure and on the excitation modes: discharges, multiplication, drift without ionizing collisions. I will select only a few topics in this broad field, referring the reader to a detailed review⁵⁾ on the subject.

In discharges, besides the characteristic atomic lines, the spectra can exhibit a broad continuum with the following three main domains, as exemplified⁶⁾ in Fig. 1: the resonance peak corresponding to the fast allowed transitions from the lowest group of excited states, the "first continuum" close to this peak, and the "second continuum" at lower energy. The resonance peak is dominant at low pressures and disappears at higher pressures, as is visible from the spectra exhibited by discharges in argon at 50 and 400 Torr (Fig. 1) and the spectra determined under conditions of electron multiplication near a wire⁷⁾ (Fig. 2) up to pressures of 20 atm. Under conditions where

Fig. 1 Samples of the emission spectra of various noble gases (from Ref. 6). Discharge excitation.

Fig. 2 Emission spectrum from argon excited by an avalanche. Wire counter: 100 μ m wire diameter, gain 10^2 . Pressure: $P = 0.1$ (curve 1), 1 (curve 2), 10 (curve 3), and 25 (curve 4) atm. 5.9 keV X-rays (from Ref. 7).

Fig. 3 VUV spectrum produced in noble gases by electrons of energies below ionization thresholds. The electrons drift in the pure noble gases at moderate electric fields, below the electron multiplication region (from Ref. 8).

no multiplication occurs, only the second continuum is visible as shown for pure noble gases⁸⁾ in Fig. 3. This corresponds, as we will see, to the operating conditions in the "gas scintillation proportional counters" (GSPCs); in this case the intensity of photon emission is nearly equal to the potential energy lost by an electron drifting in the field, divided by the average energy of the photons. This has been proved only in Xe, but probably gives the right order of magnitude for the other noble gases. It is at present widely accepted that the VUV photons in the "second continuum" are mainly due to the de-excitation of vibrationally relaxed excited molecular states

produced in three-body collisions

The time-structure properties of the emission of light are governed by the formation-time of reaction (2) and the decay-time of R_2^* . From what is known of the collision cross-section the formation-time, which is pressure dependent, is less than 100 ns at 1000 Torr. The decay-time of R_2^* ranges from 4 to 6 ns for the $^1\Sigma_u^+$ states, and reaches much longer times for the $^3\Sigma_u^+$ states, namely 3200 ns for Ar, 1700 ns for Kr, and 90 ns for Xe.

For mixtures of noble gases the spectra are radically modified by collisional de-excitation of the excited states of the host gas by guest atoms with lower energy states. This is illustrated⁹⁾ by Fig. 4, where it can be seen that at levels of Xe admixture to Ar inferior to 1% most of the photons correspond to atomic or molecular levels of Kr. The admixture of N₂ plays an important role in some detectors. The collisional transfer of the excitation energy of Ar to levels decaying rapidly with the emission of blue light in the 400 nm range is used as an efficient wavelength shifter, as illustrated⁹⁾ in Fig. 5.

Figure 6 shows the effect on the second continuum of small admixtures of CH₄ or CO₂ to Ar. One should notice that the effects are not linear. In Ar at 1 atm, the addition of the first 10⁻² Torr has the same effect as the next 25 × 10⁻² Torr. This shows that the different excited levels contributing to this continuum are not equally affected by the quencher. In detectors where mainly the fast components are active in the amplification mechanism they are certainly less affected by the quencher and we can thus understand why effects of VUV photons are still observed at much higher concentrations than those considered in these static studies.

In addition it must be stated that there exists sufficient evidence, at present, that when a multiplication process occurs in gases it can involve higher excitation than that considered in the studies so far mentioned. There exists a copious emission

Fig. 4 VUV spectrum in mixtures of noble gases. The conditions are the same as in Fig. 3 (from Ref. 9).

Fig. 5 Photon spectrum in mixtures of Ar and N₂ (from Ref. 9).

Fig. 6 Photon spectrum in Ar with the admixture of quenching agents (from Ref. 9).

Fig. 7 Spectrum of photons excited in a mixture of noble gases by a discharge. The considerable variety of lines shows that when the excitation is produced by high-temperature electrons the emission is not restricted to a few limited lines or bands (from Ref. 10).

of VUV photons not displayed on the above-mentioned spectra. This is evident from the operation of some counters in the "limited streamer mode" or some Geiger counters if we accept the generally adopted scheme of avalanche propagation by VUV photons. It is illustrated by the wealth of lines observed in a mixture of noble gases excited by a discharge¹⁰⁾ as seen in Fig. 7.

2. THE DETECTION OF PHOTONS BY GASEOUS DETECTORS

We consider only photons in the VUV or lower energy range. The new developments of gaseous detectors for photon imaging are in many respects connected with the photon-emitting processes in gases.

To detect a photon one has to absorb it with a gaseous component with a low enough ionization potential, or on a photocathode. The first approach was pioneered by Ypsilantis and Séguinot¹¹⁾ and has been developed actively for Čerenkov light imaging. Figure 8 shows the photo-ionization and absorption properties of some vapours, together with the transparency of some optical windows.

Metallic cathodes have too low a photo-ionization yield to be of practical interest. I will not mention here alkali photocathodes, whose combination with gaseous detectors has been and still is the object of active studies¹²⁾. I will only mention the liquid photocathode¹³⁾ recently invented by Anderson, which consists of a thin layer of tetrakis(dimethylamine)ethylene (TMAE -- a tetraaminoethylene) condensed on the cathode of a low-pressure multiwire chamber. Table 1 shows the properties of the various tetraaminoethylenes in the gaseous or liquid form. With ionization potentials of only 3.5 eV a considerable range of applications is at hand.

Fig. 8 a) Quantum efficiency of various vapours and transparencies of some windows. TEA: triethylamine. TMAE: tetrakis(dimethylamine)ethylene. b) Absorption cross-sections of some vapours and gases.

Table 1

Measured values of ionization potentials for several tetraaminoethylenes dissolved in trimethylsilane (Ref. 13)

Compound	I _g (gas)		E _{th} (liquid)	
	nm	eV	nm	eV
TMAE	231	5.36	350	3.54
TMB1	229	5.41	340	3.65
TBAB	221	5.60	324	3.38
TMPD	200	6.20	281	4.40

2.1 The Geiger counter

Geiger-Müller counters were at the peak of their importance in the 1930's. They were perfectly adapted to the existing level of low-sensitivity counting equipment and the difficulty of constructing stable high-voltage supplies.

In the original counter working with pure noble gases the discharge in the counter was propagated mainly by secondary effects of the ions and the photons on the cathode, releasing new generations of avalanches, with some tricks to prevent continuous discharges, such as high resistors in series or reversing voltages.

The addition of quenching vapours by Trost¹⁴⁾ was a serious progress which led to the self-quenched counters. With 10^8 ions/cm the counter delivered a pulse of nearly constant value, corresponding to the surrounding of the central wire by the ion sheath. These slow-moving ions produce a dead-time paralysing the counter for several milliseconds, in general. The discharge along the wire propagates at a speed of about 3 cm/ μ s. The inconvenient length of the dead-time and the growing availability of cheap sensitive electronics has led to the abandonment of the Geiger counter in most cases.

However, now and then interest is revived in this type of operation for projects concerned with large volumes of detectors with, for instance, 10,000 or 100,000 detecting tubes. The limitation of the discharge along the wire can be obtained by various mechanical or electrical means, thus reducing the dead region to a limited portion of the wire.

The possibility of exploiting the propagation velocity along a wire in order to localize the original avalanche has also been considered. This method, first proposed by Lauterjung and Gruhle¹⁵⁾, was studied for multiwire structures by myself and Sauli¹⁶⁾. It was indeed found that it is possible to choose the gas and the geometrical parameters in such a way that no propagation is observed from wire to wire in a multiwire chamber, but only along a single wire, with extremely easy detection of the

arrival of the streamer at the end of the wire, by a pick-up electrode. The propagation velocity is in the range of 5 cm/ μ s and is very easy to measure. Intrinsic fluctuations limit the accuracy to about 3 mm (FWHM) for 20 cm length. This is sufficient for some applications. For large detectors the dead-time is incompatible, in most cases, with the background noise.

2.2 Limited Geiger or streamer mode

Now and then it has been observed that it is possible to obtain, in wire counters, saturated pulses as in Geiger counters, but limited in time duration, in other words not connected to a propagation along the whole length of the wire¹⁷⁾. In the early study, at CERN, of the properties of multiwire chambers such operating conditions were mentioned¹⁸⁾.

The so-called magic gas, Ar + isobutane + freon was for a long time a favourite in many detectors because of the advantages of large, nearly saturated, pulses¹⁹⁾. However, no clear understanding of the mechanism was available until two independent investigations, which showed, indirectly, that the discharge mode with the magic gas could be characterized as a limited streamer mode, or a string of avalanches not reaching the cathode^{20,21)}. While these studies were of academic nature, an observation made at Saclay and CERN raised a renewal of interest for practical reasons. It was observed²²⁾ that with a proper choice of geometric parameters, fast high-current saturated pulses could be obtained, very similar to Geiger pulses, but short in time, showing that the propagation, if any, along the wire, was very limited. Photographs of the light-emitting sheath of ions around the wire confirmed this interpretation as a limited Geiger mode^{23,24)}. This was highly interesting at a time when large detectors for proton lifetime measurements were envisaged and when the rate limitations due to the localized dead-time region were of no importance. This was extensively exploited in the plastic tubes developed by Iarocci and collaborators²⁵⁾ for a large-size proton-decay detector. It was followed by a series of systematic studies by many groups clarifying the condition for a limited Geiger or a limited streamer mode.

The study of Alexeev et al.^{23,24)} showed very clearly, with photographs integrating many events, the correctness of the interpretation and the various conditions for the obtainment of these modes of operation; see Fig. 9.

The study of Atac et al.²⁶⁾, with an image intensifier showing individual events, permitted refinement of this study and confirmed the interpretation; see Fig. 10. The gas most suited to limited streamer operation is, according to these last authors, Ar + CH₄. They found that the dead-time region can be limited to 3 mm along the wire and are considering using this fact for counting of electrons in large-size calorimeters.

Fig. 9 Limited discharge modes. The propagation of a discharge in a detector can be limited along the wires or in cathode-anode space according to the geometry and the gases. The pictures show the distribution of avalanches under various conditions, integrated over many events (from Ref. 24).

Fig. 10 Self-quenching streamers at various pressures with 50% argon, 50% ethane, and 100 μ m anode wire (from Ref. 25). Single events photographed with an image intensifier.

3. THE GAS SCINTILLATION PROPORTIONAL COUNTER (GSPC)

The direct exploitation of the VUV photons followed the work of Policarpo^{5,27)} and is a technique adopted in some fields since it gives energy resolution for medium energy X-rays nearly a factor of two better than with ordinary wire chambers (7.5%, FWHM at 5.9 keV) with even better results than solid-state detectors in the energy range close to 0.1 keV.

In this detector the X-photons are absorbed in a space filled with a noble gas, and the ionization electrons drift, through a grid, to a space of a few millimetres, where a constant electric field is adjusted to produce VUV light without electron multiplication. This VUV light is converted to visible light by a thin layer of wavelength shifter deposited on the quartz window closing the chamber. This visible light is detected by photomultipliers.

The localization of the position of the initial ionization electrons can be obtained by the proper weighting of the light pulses from several photomultipliers²⁸⁾. These counters have found applications in some space experiments²⁹⁾ and have also raised interest for some medical applications as was shown by the work of Nguyen et al.²⁸⁾, where, with xenon pressures of 10 atm, a sizeable efficiency is obtained up to the region of 100 keV with a much better energy resolution than scintillation counters.

One may wonder, however, whether this type of counter is not superseded now, in all cases where localization is required, by the detector described in the next section.

4. THE "PHOTO-IONIZATION PROPORTIONAL SCINTILLATION" (PIPS) CHAMBER

It is possible to detect the VUV photons produced by ionization electrons drifting in an electric field, in a proportional wire chamber, by choosing a window transparent to the VUV photons and a gas filling with an admixture of a photo-ionizable vapour¹¹⁾, see Fig. 11. This was proposed by Policarpo³⁰⁾ and gave rise to a rapid development. The first detector based on this principle was built with a LiF window and triethylamine (TEA) vapour, whose threshold is around 7.5 eV²⁾. The energy was close to 10% (FWHM) for 5.9 keV X-rays.

Fig. 11 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 and 6.4 keV from a ⁵⁵Fe source: 7.8% FWHM (D. Anderson). Gas filling: 400 Torr Ar + 100 Torr isobutane + 0.3 Torr TMAE. CaF₂ window. Gas scintillation proportional counter with 760 Torr xenon.

Anderson³¹⁾ showed that TMAE vapour is quite advantageous for these applications. The threshold is 5.4 eV and permits the use of quartz windows. In addition the quantum efficiency is higher than 50%, i.e. better than any known solid photocathode. He obtained 7.3% (FWHM) for 5.9 keV X-rays and an imaging detector based on this principle has already been successfully tested in flight for a satellite observatory.

Although a localization accuracy of about 1 mm has been obtained in this detector³²⁾, one should keep in mind that the very low vapour pressure of TMAE (0.3 Torr at 20°) is responsible for a large mean free path for VUV photon absorption, namely 1.8 cm at 20 °C and about 1.2 mm at 30 °C, and that a very broad distribution of several centimetres width is obtained with such a device. It is the centre of gravity of the distribution which is determined with accuracy. However, for imaging of simultaneous photons in an image, this could be a serious drawback. Triethylamine, on the contrary, permits higher partial pressures, typically 25 Torr at 20° and the mean free path is only 1.5 mm. For some applications this may be an essential feature. The coupling of a scintillation xenon chamber with photo-ionizable multiwire chambers is also giving rise to active research for medical applications, where imaging detectors with a high-energy resolution is desirable in some specific cases.

5. THE SINGLE-PHOTON VUV IMAGING

The imaging of single photons in the VUV, UV, or visible range obviously plays a considerable role in many domains of science. In high-energy physics the possibility of identifying charged particles of given momentum by their Čerenkov angle in various radiators is of primordial importance. Since the first suggestion¹¹⁾ of using photo-ionizable vapours in multiwire chambers for this purpose, rapid progress has been accomplished.

Multistep structures³³⁾ have proved to be excellent tools for the detection and amplification of single electrons produced by the ionization of vapours such as TEA or TMAE. They permit higher amplifications than single-step wire chambers by reducing substantially, for a given level of amplification, the secondary electrons liberated by the photons or the ions produced in multiplicative avalanches.

A chamber with a surface of $80 \times 40 \text{ cm}^2$ is being operated in an experiment at Fermilab. It gives a two-dimensional accuracy of about 400 μm (r.m.s.). Figure 12 shows VUV images obtained with such a chamber. For cases where a considerable multiplicity of photons has to be handled simultaneously, a drift chamber making use of the large mean free path of VUV photons in TMAE (1.2 cm at 30 °C) offers a very good solution. The two-dimensional distribution is then transformed into a three-dimensional distribution. Photons very close to each other being absorbed at different depths can

Fig. 12 Images of Čerenkov light in a multistep avalanche chamber (from Ref. 31). First step: parallel gap, second step: MWPC, gas mixture Ar + CH₄ + TEA. Total gain 5×10^7 . a) Single event; b) 200 events. Čerenkov ring radius = 6.8 cm. Beam of 200 GeV pions.

be more easily detected without ambiguity. Čerenkov rings containing about 20 detected photons are easily recorded. The gas used in the drift chamber is pure methane with TMAE and, possibly, a small admixture of isobutane³⁴).

The main difficulty of the approach seems to be the copious emission of VUV photons by avalanches in methane, giving rise to parasitic photoelectrons. The multistep chamber offers interesting possibilities in the suppression or reduction of these parasitic effects. The transfer space from the first amplifying gap to the second amplifying structure can be made long enough to absorb the parasitic photons before they can reach the conversion space where the VUV photons to be imaged are absorbed. However, multistep structures are not compatible with all the gas mixtures. We have so far observed that helium + isobutane + TMAE works satisfactorily with a multistep structure and should be a good candidate. In this case a multistep structure of a large depth, say 5 cm, could easily permit the separation of photons absorbed at different depths and thus resolve large multiplicities in the Čerenkov rings into much smaller multiplicities within a narrow range of drift times.

6. THE IMAGING OF PHOTONS BELOW 1 keV BY ELECTRON COUNTING

The imaging of 1 keV electrons illustrates the possible advantages of using the photons emitted by avalanches in gaseous detectors instead of the induced charge pulses.

The detection of particles by the flash of light produced by the avalanches near a wire has been exploited in the scintillation drift chamber^{1,3,35,36}). The advantage was the much smaller effect of space-charge, since the detection is possible with a

Fig. 13 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 + CH₄ (4%) + CO₂ (5%) + N₂ (7.5%) with a drift-region field strength of $\sim 10 \text{ V cm}^{-1}$ and a gas gain of 10^6 (from Ref. 17).

smaller amplification resulting in much higher possible rates. However, the intrinsic duration of the light pulses limited the particle separation to nearly the same value as with the use of the charge-induced pulses. Siegmund et al.³⁷⁾ showed that, by a proper mixture of N₂ and quenching agents with Ar, it is possible to reduce the pulse width of the light flashes produced by avalanches in a gap limited by parallel grids to 2 ns only, almost a factor of ten better than with the induced pulses. By absorbing the X-rays in a conversion space with a low electric field transferring electrons to the amplifying gap it is possible to separate, with a photomultiplier, the pulses produced by individual electrons (Fig. 13). The energy resolution is then limited only by the fluctuations in the gain.

Up to 1 keV this method seems promising and gives the ultimate possible resolution with a gaseous detector. We have shown, at CERN³⁸⁾, that the UV light produced in such a mixture, which is essentially due to the addition of N₂, can be conveniently converted, with almost 100% yield, by a plastic wavelength shifter, thus permitting very flexible geometrical structures.

7. THE DETECTION OF PHOTONS WITH A LIQUID PHOTOCATHODE IN A MULTIWIRE CHAMBER

Anderson¹³⁾ has investigated the possibility of detecting photons with liquid TMAE condensed on the cathode of a multiwire chamber. Table 1 shows that liquid tetra-aminoethylenes permit reaching a photo-ionization threshold as low as 3.5 eV. The first tests with condensed TMAE showed that a quantum efficiency of 1% was achieved with a threshold at about 4.2 eV. Interesting applications appeared immediately from the observation that a BaF₂ scintillator emits photons detectable by this photocathode.

An efficiency of about 50% was achieved with 0.6 MeV γ -rays and this may offer interesting applications for positron cameras. At energies in the GeV range the energy resolution can be quite good; and this first happy marriage of a high-density scintillator, of only 2.2 cm radiation length, with a multiwire chamber offers great prospects for photon calorimeters, since the spatial development of a shower can be obtained together with the total energy loss.

8. CONCLUSIONS

Developments of recent years show that the gaseous detectors of the multiwire type, or with amplification between parallel grids, permit a considerable extension of their applications, owing to the progresses made in the detection of single photons of energies ranging from 4 to 10 eV.

The detection of the VUV photons emitted by scintillation gaseous converters permits an improved energy resolution in imaging X-ray detectors.

The detection of VUV photons from Čerenkov light permits a serious progress in particle identification.

The detection of the scintillation light from BaF_2 crystals permits the development of a new class of calorimeters.

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