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**INVESTIGATION OF LIGHT EMISSION
FROM A PARALLEL-PLATE AVALANCHE CHAMBER
FILLED WITH NOBLE GASES AND WITH TEA, TMAE, AND H₂O VAPOURS
AT ATMOSPHERIC PRESSURE**

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ABSTRACT

The light emission from avalanches in parallel-plate chambers, filled with noble gases and with TEA, TMAE, and H₂O vapours at a total pressure $p = 1$ atm under the condition of low gas gain, has been investigated. Three important results have been obtained.

- i) At partial pressures of more than a few Torr, and for a given charge gain, the light output from TEA, TMAE, and H₂O in the spectral region 200–700 nm is the same as that from all other known quencher gases, considered to be the maximum.
 - ii) For these vapours, the ratio of light to charge is independent of their concentration when their partial pressure is more than a few Torr.
 - iii) The best energy resolution achieved with the light-emitting chamber is $\sim 18\%$ for 5.9 keV.
- Qualitative models explaining these results are given.

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1. INTRODUCTION

During the last few years, light emission from Townsend avalanches has been used successfully for the optical readout of parallel-plate avalanche chambers (PPACs) (see, for example, refs. [1] to [3]). It was found that two mixtures give maximum light emission: argon + triethylamine (TEA), and argon + tetrakis(dimethylamine)ethylene (TMAE). The light-to-charge ratio achieved its maximum at low gain. This gave the idea for a three-step chamber [4] in which electrons, after amplification, transfer to the gap where only a small amplification occurs, thus producing more light. A systematic study of light emission at low pressure and high gas gain has been made in ref. [2]. However, in the case of mixtures at atmospheric pressure, no such studies had yet been made. The aim of this work is to investigate the light emission from avalanches in PPACs filled with noble gases and with TEA, TMAE, and ethyl ferrocene (EF) at $p = 1$ atm under the condition of low gain (in order to optimize three-step chambers), and to understand the physical excitation mechanism of these mixtures.

2. EXPERIMENTAL SET-UP

The construction of the PPAC has been described in ref. [1]. Light emission from the chamber was investigated using an amplification gap width of 1.5 mm. The chamber was flushed with noble gases, either pure or in mixtures containing methane, at $p = 1$ atm, with (or without) TEA, TMAE, H₂O, or EF vapour. The body of the PPAC and the whole gas system can be heated up to 70 °C. The avalanches were initiated by an α -source inside the chamber. Signals from the mesh were recorded by a charge-sensitive amplifier.

Two set-ups were used to investigate the light emission of avalanches in the region of 180–760 nm. In the first, a Jobin-Yvon H20 ultraviolet-light monochromator was coupled to the chamber, as described in ref. [1]. The light entering the monochromator through a CaF₂ window was recorded by a photomultiplier (PM). After amplification and shaping, the coincidence signals from the PPAC and the PM were sent to a scaler.

In the second set-up, the PM was coupled directly to the PPAC, and the signals from the PPAC and the PM were sent to pulse-height analysers. The distribution showed sharp peaks, the centre of which, at each given high voltage in the PPAC, we define as the mean value of charge or light. In such a way we can measure the collected charge and light as functions of the applied voltage.

3. RESULTS

3.1 Pure argon

To carry out a systematic study of light emission, we started our experiments with pure Ar. However, in order to ensure that the Ar in the PPAC was as clean as possible, it was necessary to flush the chamber with Ar during a few days, at a rate of ~ 50 l/h. In this case the maximum gas gain achieved was about 3; above this value, discharges appeared. In the emission spectrum of this gas, only a small trace of OH⁻ emission was present, with a peak intensity at $\lambda = 310$ nm (fig. 1). We assume that OH⁻ emission is due to the dissociative excitation of water vapour [5, 6], because small

traces of water are normally present in a gas system, unless special precautions are taken. The emission of a second Ar continuum at $\lambda = 200$ nm [7], which would correspond to the excitation of higher levels of Ar₂ molecules, was not found.

When the flux was reduced, the gain could reach $\sim 10^2$ because of the quenching effect of impurities, and the water emission became stronger.

3.2 Noble gases + TEA

Measurements taken using the monochromator (first set-up) showed that with small concentrations of TEA (partial pressure $p_{\text{TEA}} \leq 0.5$ Torr) the emission comes from both water (310 nm) and TEA (280 nm) bands. At $p_{\text{TEA}} = 0.5$ Torr, the intensity of the H₂O band is about 25% of that of the TEA band, and this fraction increases with decreasing p_{TEA} . At $p_{\text{TEA}} > 0.5$ Torr, the emission consists basically of the strong TEA band at $\lambda = 280$ nm (see fig. 2). The typical dependence of the integral intensity of this band, measured by the PM (second set-up), and of the gas gain on the voltage between the meshes, is given in figs. 3. Figure 3a presents the results for the full range of applied voltages; Fig. 3b shows, in more detail, the region before multiplication starts.

Using these data, we can calculate the light-to-charge ratio as a function of the gas gain. Typical results of our calculation are presented in fig. 4, where, for comparison, we also give the light-to-charge curves for Ar. Remarkably, the light output of this gas (basically from water emission) is only two to three times less than the maximum emission achieved with a mixture of Ar + TEA. The intensity in the 280 nm band as a function of the concentration of TEA is given in fig. 5. It can be seen that the light-to-charge ratio is not dependent on the TEA concentration when this is more than 5 Torr ($> 1\%$).

For a mixture of Xe + TEA, the emission spectrum and the behaviour of the light-to-charge ratio were the same as in the case of Ar + TEA (see fig. 5). The long wavelength tail of the first molecular Xe continuum ($\lambda > 185$ nm) was not recorded. With Xe + TEA at partial pressures greater than 12 Torr, we observed a saturation of the light-to-charge ratio at a value that is about twice as much as that for Ar.

3.3 Noble gases + TMAE

In the case of a mixture of noble gases and TMAE vapour, the emission spectrum (480 nm) consisted basically of the TMAE band. The light-to-charge ratio at a gain of 100 for different noble gases and for different partial pressures is given in fig. 6. This figure clearly shows the tendency to saturation at $p_{\text{TMAE}} > 7$ Torr, as in the case of TEA. At this pressure, the light-to-charge ratio in Ar + TMAE achieved the same level as that for Ar + TEA. This indicates that at the same partial pressure the scintillation efficiency of TEA and TMAE vapours is about the same. This fact is very important because TMAE emission is in the visible region, which greatly simplifies the optical readout. From fig. 6, it can also be seen that the light-to-charge ratio increases with the atomic weight of the noble gas.

3.4 Noble gases + CH₄ + TMAE vapour

In practice, in order to obtain more charge gain by using the optical readout and to stabilize the multiplication process, it is usual to add some percentage of CH₄ to the Ar + TMAE mixture. As described in ref. [1], the addition of 10% CH₄ to the Ar + TEA does not change the light-to-charge ratio very much. In the case of TMAE, however, the ratio drops steeply [1]. Unfortunately, as the measurements were done with different concentrations of TEA and TMAE, new measurements have had to be made at the same partial pressure for both, and the results compared.

The light-to-charge ratio for mixtures of noble gases with CH₄ and for different TMAE partial pressures is given in fig. 7; it can be seen that this ratio increases with p_{TMAE} . In the case of Ar + CH₄ (10%) + TMAE (at 7 Torr), the light-to-charge ratio reaches the level of that of Ar + TEA, which is very important from the practical point of view. At the same p_{TMAE} , the light-to-charge ratio increases slightly with the atomic weight of the noble gas used.

3.5 Investigation of the water emission

As mentioned above, the intensity of the emission band of water vapour, which in the gas system is present as an impurity, is rather strong. It is this fact that has stimulated the investigation of light emission from different gases containing water vapour. In these experiments, the TMAE bubbler is replaced by a bubbler filled with water, and by using a bypassing technique the H₂O concentration can be varied over a wide range.

3.5.1 Ar or Ar + CH₄ with water vapour

In Ar with saturated water vapour at room temperature and at $p_{\text{H}_2\text{O}} \approx 20$ Torr, the chamber did not work, owing to current leakage on the dielectric surface. When the pressure of the water vapour was below the saturation point, the light-to-charge ratio was exactly the same as that for Ar + TEA, but the maximum charge gain achieved was only about 3 to 5. In the case of a mixture of Ar + CH₄ + water vapour, the maximum gas gain was ~ 15 , but the light-to-charge ratio dropped by a factor of 25 to 80, depending on the water and CH₄ concentrations. Therefore, in order not to reduce the H₂O emission too much, only a small concentration of strongly quenching gas should be added. However, as a small amount of CH₄ does not make a good enough quencher, it is necessary to add very small concentrations of another, more efficient, quenching gas so as to be able to increase the gain.

3.5.2 Ar + H₂O + ethyl ferrocene

The investigation described earlier [8] shows that EF is one of the best candidates for a good quencher. Moreover, the vapour pressure of EF at room temperature is about 10^{-2} Torr, and it does not interact with air, or with metals, dielectrics, or other materials. As the ionization potential of EF is about 6 eV, it can be used as a photosensitive medium, like TEA or TMAE. For this reason, we have measured the light emission in Ar + H₂O + EF. It was found that the spectrum contained only the OH band (310 nm), and no other peak was recorded. In order to see a spectrum of EF, we tried to remove the water contamination from the gas, from the gas system, and from the EF itself. To do

this, the gas system and the EF were heated to a certain temperature T_{EF} . They were then flushed during 24 hours, at this fixed temperature, by passing Ar through silica gel, after which the measurements were made. The value of the water emission peak as a function of T_{EF} is given in fig. 8. Although this intensity drops and the EF vapour pressure increases with T_{EF} even at 70 °C, we did not record any emission, except that of OH. In another series of experiments, we increased the water concentration in the system artificially. For this purpose, the bubbler containing H₂O was used in parallel with the EF bubbler. We started with a mixture of Ar + EF, then slowly increased the H₂O concentration. The light-to-charge ratio increased slightly, but the value of the maximum gas gain dropped. It seems that the Ar + EF mixture, with the natural impurity of water, is an optimum choice.

Results obtained at room temperature are presented in fig. 4. As can be seen, in the case of Ar + EF the light-to-charge ratio is four times less than for Ar + TEA and almost exactly the same as for Ar + TMAE at room temperature. The maximum charge gain achieved is also the same as in Ar + TMAE at room temperature. When the temperature of the EF was increased to 60 °C, the results obtained were similar to those for TMAE. For example, in fig. 9 the light-to-charge ratio for the emission from water is plotted as a function of partial pressure. It can be seen that at $p_{H_2O} \approx 2$ Torr it achieves saturation, as in the case of TEA or TMAE. Therefore, mixtures of Ar + EF with water vapour give exactly the same results as Ar + TMAE, and will probably find a wide application.

4. MEASUREMENTS OF THE ENERGY RESOLUTION OF LIGHT-EMITTING CHAMBERS

As a result of the measurements described above, we found that three vapours—TEA, TMAE, and H₂O—have approximately the same light output when introduced into a chamber at a partial pressure of approximately a few Torr. Compared with all the other gases that have been tested (see, for example, ref. [1]), these vapours show maximum light output in the spectral region of 200–700 nm. At the same time, they allow a rather high gas gain to be achieved, and thus are optimal for imaging chambers. But it would be very attractive for light-emitting chambers to have the possibility of measuring not only the coordinates of particles (or X-ray photons) but also their energy from the brightness of the avalanches. As was first shown in ref. [9], in principle this is possible: the energy resolution achieved in these earlier measurements was about 25% for 5.9 keV and a gain of 10^4 . We have tried to find out what is the highest energy resolution that can be achieved with maximum light collection and optimal gas conditions, and with a low gain (about 1–5) which, as is well known [10], is favourable to good energy resolution.

4.1 Modification of the chamber

As has already been pointed out in ref. [1], the light-to-charge ratio increases with the gap width. For most of the measurements described in ref. [4], the gap was ~ 1 cm. So for our present measurements we have used the same PPAC, but increased the gap between the last two meshes (amplification region) from 1.5 mm to 1 cm and then up to 2 cm. The ²⁴¹Am source was replaced by a well-collimated ⁵⁵Fe source. The PM was placed very close to the CaF₂ window of the wire chamber,

at a distance of ~ 6 mm. Measurements were made with Ar + TEA and Ar + TEA + CH₄ at pressures of ~ 1 atm and for different concentrations of TEA and CH₄.

4.2 Results

The best result was obtained with Ar + TEA (at 70 Torr) and a gap width of 1 cm. The intensity of TEA emission and energy resolution measured in this mixture by the PM, as a function of applied voltage, is shown in fig. 10. As can be seen, the energy resolution improves with the applied voltage, but at $V = 6.5$ kV, multiplication starts, which of course (see ref. [10]) spoils the energy resolution. The best energy resolution obtained was about 18%, which is 1.4 times better than in an earlier experiment [9].

5. DISCUSSION

It is normally very complicated to explain the mechanism of light emission in imaging chambers because of the many processes—and even chains of processes—that are involved. But in the case of a small gain (i.e. a low ratio of E/p), the situation is rather simpler because many of the processes will not take place.

To explain all the results described above, let us consider the model of light emission produced by electrons in a gas at a low E/p . This model, which was worked out in detail and checked experimentally, is generally accepted; a description of it can be found in any modern book on discharge in gases, for example in ref. [11].

5.1 Pure gas

5.1.1 Drift of a single electron

In this case, the single electron gets energy from the electric field and loses it during collisions with the atoms and molecules of the gas. In some instances the elastic collision can be neglected because the energy loss is proportional to the ratio m_e/M , where m_e and M are the masses of the electron and the atoms (or molecules), respectively. So in a first approximation, inelastic collisions are much more important. Figure 11a shows the typical behaviour of excitation (σ^*) and ionization (σ^+) cross-sections for atoms as a function of electron energy. In a moderate electric field of less than 10 kV/cm·atm, there would be a much greater probability of excitation than of ionization. Indeed, imagine that in this graph an electron moves slowly to the right in energy scale. When the kinetic energy E_k achieved is sufficient to excite the atom (point A in fig. 11a), the electron will then lose this energy over a distance $\lambda^* \approx 1/n\sigma^*$, where n is the number of atoms (in cm^{-3}). It will then go back to zero on the energy scale (arrow in fig. 11a), and the above process will start all over again. Because of this process, there is only a very small probability of achieving enough energy for ionization, $E_k \approx E^+$. But even if the energy needed for ionization were reached (points B and C on fig. 11a), the excitation probability would still be much greater than the ionization probability. So in moderate electric fields the electrons will only excite. This means that the number of excited atoms (molecules) or photons per electron will be rather high. Nevertheless, ionization is possible through the process $A^* + A \rightarrow A_2^+ + e$, where A is an atom of a noble gas (see, for example, ref. [12]).

Noticeable direct ionization resulting from electron impact is possible when the electrons move very rapidly on the energy scale, so that the energy reached between two collisions is enough for ionization to take place. This occurs if the electric field is about 10^5 V/cm·atm. [The maximum ionization cross-section is about 10^{-16} [13], as shown in fig. 11b, so at 1 atm, $\lambda_{\min}^+ = 1/(10^{19} \times 10^{-16}) \approx 10^{-3}$ cm, and the electron must have an energy of ~ 100 eV.] When the electron reaches a kinetic energy $E_k \gtrsim 100$ eV, the probabilities of excitation and of ionization become comparable. Thus the number of photons produced by an electron is small. Such conditions are found in low-pressure gas chambers or around the thin wires in multiwire proportional chambers (MWPCs) at normal pressure.

5.1.2 A group of electrons in an electric field

In the case of a group of electrons (concentration n_e/cm^{-3}), the probability of ionizing the atoms increases for a given electric field and for each individual electron, which is not the case for a single electron. This is because electrons in a group can exchange energy between themselves, which leads to some of them having an energy much higher than average, owing to the tail of the electron energy distribution. The energy in this tail can be sufficient to cause direct ionization. But in reality, the tail starts to be cut very sharply at the first excitation potential [14]. For example, in a positive column of glow discharge, where the electric field is rather high (~ 10 V/cm·Torr $\approx 7.6 \times 10^5$ V/cm·atm), the tail can be cut by more than one order of magnitude. The ionization results basically from the collision of excited atoms (molecules) with the electrons, which have rather low energy. Even in the case of thermodynamic equilibrium, which is more favourable for tail formation, the number of electrons with $E_k > E^*$ is a few orders less than expected from the Maxwellian distribution [15]. So even in the case of gas discharge, the ionization rate is much less than the excitation rate.

5.2 Mixture of gases

5.2.1 Drift of a single electron

Let us consider a mixture of two gases, one having a high excitation energy E_{basic}^* (the main constituent) and the other a lower excitation energy E_{imp}^* (the impurity) and ionization energy E_{imp}^+ (fig. 11c). Suppose that the number of atoms (or molecules) per cubic centimetre were to be n_{basic} for the first gas and n_{imp} for the second gas. In this case, the kinetic energy of the electron drifting in the electric field would increase continuously until it was lost to the excitation of the basic constituent or of the impurity gas. For a concentration of impurity gas with $n_{\text{imp}} \geq n_{\text{basic}}$, all excitation and ionization phenomena would be exactly as described in subsection 5.1. But when $n_{\text{imp}} < n_{\text{basic}}$, the basic gas can, in principle, start to play a role if the excitation and ionization cross-sections are of the same order of magnitude.

Let us consider this situation in more detail. In the case of a very weak electric field, where the mean free path for energy lost to excitation of the impurities is less than the distance in which the electrons acquire sufficient energy to excite the basic gas, only the impurities can be excited and ionized (fig. 11c). The criterion for this is

$$\frac{L}{V/E_{\text{imp}}^*} < \lambda_{\text{imp}}^* \quad (\text{for } E_k \approx E_{\text{imp}}^*),$$

where L is the width of the amplification gap, V is the applied voltage, and $\lambda_{\text{imp}}^* = 1/\sigma_{\text{imp}}^*(E_k \approx E_{\text{imp}}^*) \times n_{\text{imp}}$.

In the case of a very strong electric field, the electron can easily reach sufficient energy to excite the basic gas. The excitation rate of the impurities would be equal to $\sigma_{\text{imp}}^*(E_k \approx E_{\text{basic}}^*) \times n_{\text{imp}}$, and the excitation rate of the basic gas would be $\sigma_{\text{basic}}^*(E_k \approx E_{\text{basic}}^*) \times n_{\text{basic}}$. Because $\sigma_{\text{imp}}^*(E_k \approx E_{\text{basic}}^*) \gg \sigma_{\text{basic}}^*(E_k \approx E_{\text{basic}}^*)$ (fig. 11a, point B), the basic gas starts to be excited when $n_{\text{imp}} \ll n_{\text{basic}}$. An estimate of this, given in ref. [12], shows that normally $n_{\text{imp}}/n_{\text{basic}}$ must be less than 10%. It is the only case where the excited states of the basic gas start to play a role: they can emit vacuum ultraviolet (VUV) photons or transfer their excitation energy to the impurity molecules by collisions, and so on, which greatly complicates the explanation.

5.2.2 A group of electrons

Even in the case of a group of electrons it is very difficult to excite the basic gas. As mentioned in subsection 5.1.2, a more favourable situation is that of thermodynamic equilibrium. Calculations based on Sakhar equations [11] (Maxwellian distribution) show that if for the fixed electron temperature T_e in the clean basic gas (without any impurities) the electron concentration were to be n_e^{clean} , then in the mixture of gases the new electron concentration would be $n_e^{\text{mixture}} > n_e^{\text{clean}}$. This is basically due to the ionization of the impurities. In this case the number of electrons given by the basic gas would be $n_e^{\text{basic}} \ll n_e^{\text{clean}}$. As already mentioned (subsection 5.1.2), the Maxwellian distribution is not realized in a real situation, because of a cut-off in the tail of the electron distribution. In this case, the contribution of the basic gas to excitation and ionization would be considerably less. In an electric field of ≤ 1 kV/cm·atm, the basic gas can be excited only when the concentration of impurities is less than 10^{-2} %. In an electric field of ~ 10 kV/cm·atm, the basic gas can be excited when $E_{\text{basic}}^* - E_{\text{imp}}^* \leq$ a few eV, and $n_{\text{imp}}/n_{\text{basic}} <$ a few per cent.

The investigations described in ref. [11] show that in the case of a gas mixture, only the impurities with the smallest ionization potential would be basically excited and ionized. It is only when the concentration of impurities is very small, $< 1\%$, or in very strong electric fields of $\geq 10^5$ V/cm·atm, that the direct ionization of the gas with high ionization potential occurs.

6. EXPLANATION OF LIGHT EMISSION IN PPACs AND WIRE CHAMBERS

We will try to explain all the results from studies of light emission in PPACs or in wire chambers.

According to the results described here, we assume that in PPACs using mixtures of noble gases with H_2O , TEA, or TMAE, and operating in an electric field of typically a few kV/cm·atm, it is basically the additive that would be excited. This was very well confirmed in practice, because the emission spectrum contained only the band of the impurities, even when their concentration was small. When there are small concentrations of impurities, excited states of Ar_2^* and Xe_2^* are deactivated, basically by radiation. Therefore if the number of these excited molecules is high

enough, we will record at least a first molecular continuum. At high concentrations of impurities, deactivation of the excited molecules Ar_2^* and Xe_2^* can occur through inelastic collision with the molecules of TEA, TMAE, or H_2O vapours. Let us consider a PPAC with a distance L between the electrodes, with an applied voltage V , and assume that the electric field is ≤ 10 kV/cm · atm. There are two limiting cases: i) a small concentration of TEA or TMAE ($\lambda^* \gg L$); ii) a high concentration of TEA or TMAE ($\lambda^* \ll L$).

i) $\lambda^* \gg L$

In this case (and when $n_{imp}/n_{basic} > 0.1\%$), then the number of photons created by each individual electron should be proportional to the number of collisions with impurity molecules having the smallest ionization potential (because at $n_{imp}/n_{basic} > 0.1\%$, only the impurities play a role). So the number of photons emitted per electron would be proportional to n_{imp} . This was clearly observed in our experiment (see figs. 5 and 6), when the partial pressure of the vapours was less than a few Torr.

ii) $\lambda^* \ll L$

Suppose that the gas gain in the chamber is $A = 2^n$. In this case, the distance between the successive ionizing collisions is $\lambda^+ = \Delta x = L/n$ and the voltage drop is $\Delta V = V/n$. Each individual electron can produce light at this distance (the maximum value is achieved when $\lambda^* = 1/n\sigma^* < \Delta x$, as mentioned above, and $\lambda^+ > \lambda^*$). The number of photons ΔI would be

$$\Delta I = \frac{K \cdot \Delta V}{E^*},$$

where E^* is the mean energy necessary for excitation, and K is a constant that depends on the applied voltage and the gas composition.

The full intensity produced by all electrons would be

$$I = \frac{K \cdot \Delta V}{E^*} (1 + 2 + 2^2 + 2^3 + \dots + 2^n).$$

The light-to-charge ratio (I/Q) would be

$$\frac{I}{Q} = \frac{K \cdot \Delta V}{E^*} \frac{1 + 2 + 2^2 + \dots + 2^n}{2^n} \approx \frac{2VK}{nE^*}. \quad (1)$$

As can be seen,

$$\frac{I}{Q} \approx \frac{KV}{n}, \quad K \ll 1,$$

and qualitatively this works in practice (see figs. 5 and 6). For some gases it is possible to calculate the value KV/nE^* analytically, but it is much simpler to use a semiempirical method. Using this method, it is easy to explain the dependence of I/Q as a function of the TEA or TMAE partial pressure. Let us

demonstrate it with one example. Estimates show that when p_{TEA} increases from 0.5 to 60 Torr, for a given charge gain, $I/Q = KV/nE^* \approx \text{const}$. This is because V increases, with p_{TEA} compensated by increasing E^*/K . For example, at

$$p_{\text{TEA}} \approx 0.5 \text{ Torr}, \quad V \approx 300 \text{ V (see fig. 4a)} \quad \text{and} \quad \frac{E^*}{K} \approx \left(\frac{dI}{dV}\right)^{-1} = \frac{1}{10} \text{ (see fig. 4b)},$$

and at

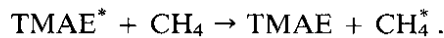
$$p_{\text{TEA}} = 60 \text{ Torr}, \quad V = 1200 \text{ V} \quad \text{and} \quad \frac{E^*}{K} \approx 1/2.5.$$

At $p_{\text{TEA}} < 0.5$ Torr, I/Q would decrease slowly because V would become smaller, whilst there would be a noticeable increase of E^*/K (see fig. 3b).

As mentioned above, in a first approximation we can neglect elastic collisions, but it should be taken into account in the second approximation. Suppose that the electrons drift in a uniform electric field and have only elastic collisions with the atoms of the gas. Let us consider a hypothetic atom with a single excitation level E^* (the same would be true for an atom or molecule with many levels). When the electron undergoes a voltage drop of E^* , its kinetic energy has the value $E^* - \Delta E$, where E^* is the first excitation potential and ΔE is the energy lost in the collision. In the case of infinitely heavy atoms, which can be considered as elastic balls, $\Delta E = 0$. In other cases $\Delta E > 0$, and its value would increase with decreasing atomic weight of the gas. Direct confirmation of this is given by the fact that the calculated kinetic energy of an electron, drifting in the electric field, depends on the atomic weight of the noble gas (see, for example, refs. [16] and [17]). So at a given voltage (or a given length), the amount of excitation would be equal to $V/\Delta V$, where ΔV is the voltage drop that is necessary to obtain E^* , and thus would be slightly dependent on the atomic weight of the noble gas.

Let us comment on the results obtained with three-component mixtures: noble gas + quencher (such as CH_4) + TMAE (or TEA). As we mentioned earlier, the electron energy distribution is cut at the lowest excitation potential of the gas. In the case of $\text{Ar} + \text{CH}_4 + \text{TMAE}$ (or TEA), both gases— CH_4 and TMAE (or TEA)—will contribute strongly to the cut-off of the tail of the distribution function. But TMAE and TEA probably contribute more, because they have the lowest ionization potential. If we also assume that TMAE (TEA) has a larger total cross-section for excitation than has CH_4 , then TMAE (TEA) will play the main role even at smaller concentrations. This means that at small concentrations of TMAE (TEA), its excitation would not be sufficient because the distribution function would be cut at the CH_4 levels. But at rather high concentrations of TMAE (TEA), the cutting will be at the TMAE (TEA) levels, so this gas can be excited efficiently.

Another possible influence of CH_4 on TMAE (TEA) emission is de-excitation. This process can follow from



If such a process occurs, then the probability for each fixed TMAE molecule to de-excite will be $n_{\text{CH}_4}\sigma_{\text{de-excit}}$, i.e. proportional to CH_4 . If this process were to dominate, then the intensity of TMAE emission would always be proportional to n_{TMAE} , which was not observed in practice.

6.2 Explanation of the results of other authors

The light-emission model described in ref. [11] makes it possible to explain all the known results concerning the emission of visible or VUV light from wire chambers and PPACs at $p = 1$ atm.

For example, some authors [18] have investigated light emission in a single-wire counter in which the diameter of the wire can be varied from 1 to 0.08 mm. In this case, the strength of the electric field near the wire can be varied by at least one order of magnitude. Measurements were made in mixtures containing a noble gas and with different quenchers. It was found that in the case of a thick wire, only impurities were excited. Noble-gas lines were excited only in the case of a thin wire. This experiment has its explanation in the frame of the emission model.

In the work of ref. [4], it was found that the value of the light-to-charge ratio in PPACs was much more than in MWPCs. The explanation could be the following. In PPACs with a gap $L \gg \ell^*$, emission would obey Eq. (1). In wire chambers at atmospheric pressure, all multiplication processes start near the wire, in the region < 0.1 mm. In this case, $L \approx \ell^*$, and according to our model the emission must therefore be less. The situation would be much more dramatic for the last free path of the electron before ionization ℓ^+ (which unfortunately made the largest contribution), because in high electric fields $\ell^+ \approx \ell^*$, and independently of ΔV the number of excited atoms and molecules produced would be ~ 1 . To prove this, let us consider in more detail the processes that occur over the distance ℓ^+ near the wire. As an example, let us take the case of noble gases, for which all the cross-sections are well known. The mean free path before excitation is

$$\ell^* = 1/n\sigma^* .$$

At 1 atm, the value of ℓ^* would be smallest when σ^* is largest. For noble gases, the maximum value of σ^* is about 10^{-16} cm² (see, for example, ref. [13]), and it achieves this at $E_k \approx 100$ eV; which means that at 1 atm, $\ell_{\text{min}}^* \approx 10^{-3}$ cm. The voltage drop calculated over this distance, near a wire of 20 μm diameter, is about 100 eV. The number of elastic collisions would be few for He, and about 10 for other noble gases. At each collision the energy loss would be $\sim m_e/M$, so we can ignore it. Therefore an electron can reach an energy of ~ 100 eV before excitation. At this energy, $\sigma^+ \approx 10^{-16}$ cm², so $\ell^* \approx \ell^+$ and the electron excites only once before ionization. If we take, for our estimate, σ^* less than maximum—for example $\sigma^* \approx 10^{-17}$ cm²—then the voltage drop along the mean free path will be larger. Again, the elastic collisions can be neglected, and this means that the kinetic energy would be more than 100 eV. But at $E_k > 100$ eV, $\sigma^+ \approx \sigma^*$ (see fig. 11b and ref. [13]), so the amount of excitation would be approximately equal to the amount of ionization, i.e. the light-to-charge ratio would be about 1. We expect that in the case of the mixture Ar + TEA (or TMAE), in small concentrations, the physical picture described above does not change very much. According to theory, in a high electric field of the order of 10^5 V/cm·atm, the tail of the electron distribution

function would not be severely disturbed. This means that TMAE will change the distribution function when $\sigma_{\text{TMAE}}n_{\text{TMAE}} \approx \sigma_{\text{Ar}}n_{\text{Ar}}$ at $E_k > 15$ eV. Even if we assume that $\sigma_{\text{TMAE}} \approx 10^{-14}$ cm² (which is unrealistic), $n_{\text{TMAE}}/n_{\text{Ar}} \approx 1\%$.

Let us make a few comments about light emission at low pressure. In the case where a typical voltage is about 1 kV and the pressure is ~ 10 Torr, this corresponds to $E/p \approx 10^5$ V/cm·atm. So the situation would be exactly the same as that near the thin wire at $p = 1$ atm. This explains why, at low pressure, the light-to-charge ratio is much less than at 1 atm [19]. The energy of the electrons, as estimated above, is expected to be ~ 100 eV. More accurate calculations made in ref. [20] confirm this conclusion. Experimentally, photons with an energy of ~ 100 eV emitted from the low-pressure detector have been observed [21]. At this energy, there is not only direct ionization of TMAE, but also direct ionization of Ar. This can initiate complicated chains of interaction between Ar and TMAE. Furthermore, dissociative excitation can start to play a role in the excitation process of TMAE when, in the emission spectrum, not only TMAE bands but also C, H, and other lines are present [5]. Therefore many processes can take place, and this is the most complicated case from the point of view of theoretical analysis. But in any case, because $\lambda^+ \approx \lambda^*$, the number of photons produced is very small.

6.3 Energy resolution

As is well known (see, for example, ref. [22]), the best energy resolution in the gas detectors is achieved at a gain of 1 and decreases with the gas gain, and it is on the basis of this that the so-called proportional gas scintillation counters were constructed. Such detectors usually have the geometry of a PPAC with a gap of ~ 1 cm. For pure Xe at $p \approx 1$ atm, the applied voltage of this gas is usually about $V \approx 6$ kV. The estimated total number of photons emitted by one electron was about $N_{\text{ph}} = V/E^* \approx 6 \times 10^3$ V/10 eV ≈ 600 . The best energy resolution achieved is about 8% for 5.9 keV [23].

In our experiments with Ar + TEA, $N_{\text{ph}} = kV/E^*$ is about 4–6 at $V \approx 800$ V, which means that at $V \approx 6$ kV, we will have one order less of photons than was the case with gas scintillation counters. This explains why, in our voltage range, the measured energy resolution was very bad: 50–30%. At higher voltages, amplification appears. On the one hand, this spoils the energy resolution, but on the other hand it increases the light output, and as a result, the measured energy resolution improves. According to ref. [10], the best energy resolution that can be achieved with gas amplification (in a single-wire counter) is about 11%. Our result of 18% is worse than this, but it is better than our first results [9].

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Figure captions

Fig. 1 Emission spectrum from the PPAC flushed with Ar at ~ 50 l/h. The peak at $\lambda = 310$ nm corresponds to water emission; the peak at $\lambda = 620$ nm is the second-order diffraction of the monochromator, at which the spectral resolution is twice as high.

Fig. 2 Typical emission spectrum from Ar + TEA mixtures. The peak at $\lambda = 280$ nm corresponds to TEA emission; the peak at $\lambda = 560$ nm is the second-order diffraction of the monochromator, at which the spectral resolution is twice as high. A small trace of water emission can be seen there.

Fig. 3a Charge gain (2 and 4) and light emission (1 and 3) as a function of voltage: (1) and (2) Ar + TEA (0.5 Torr), (3) and (4) Ar + TEA (60 Torr), all at a total pressure $p = 1$ atm.

Fig. 3b Emission of light by electrons as a function of voltage at gas gain ≈ 1 in mixtures of Ar + TEA, all at total pressure $p = 1$ atm but at different partial pressures (in Torr):

- | | | |
|---------|---------|-------------------|
| (1) 0.5 | (4) 7.5 | (7) 60 |
| (2) 3 | (5) 15 | (8) High gas flow |
| (3) 4 | (6) 40 | (9) Low gas flow |

Fig. 4 Dependence of the light-to-charge ratio on the charge gain for different mixtures, all at total pressure $p = 1$ atm but at different partial pressures (in Torr):

- | | |
|-----------------------------|---------------------------------------|
| (1) Ar + TEA (60) | (4) Ar + TEA (0.5) |
| (2) Ar + TMAE (0.4) | (5) Pure Ar |
| (3) Ar + EF ($< 10^{-2}$) | (6) Ar + H ₂ O vapour (10) |

In the spectrum of Ar + EF, owing to water impurities, only the water peak at 310 nm is presented. When the H₂O concentration was increased artificially, the light-to-charge ratio also increased but the gas gain dropped.

Fig. 5 Dependence of the light-to-charge ratio on the partial pressure of TEA for (1) Ar + TEA and (2) Xe + TEA, at a gas gain of 100.

Fig. 6 Dependence of the light-to-charge ratio on the partial pressure of TMAE for (1) Ar + TMAE; (2) Ne + TMAE; (3) He + TMAE at a gas gain of 100.

Fig. 7 Dependence of the light-to-charge ratio on the partial pressure of TMAE, at a gas gain of 100 and for:

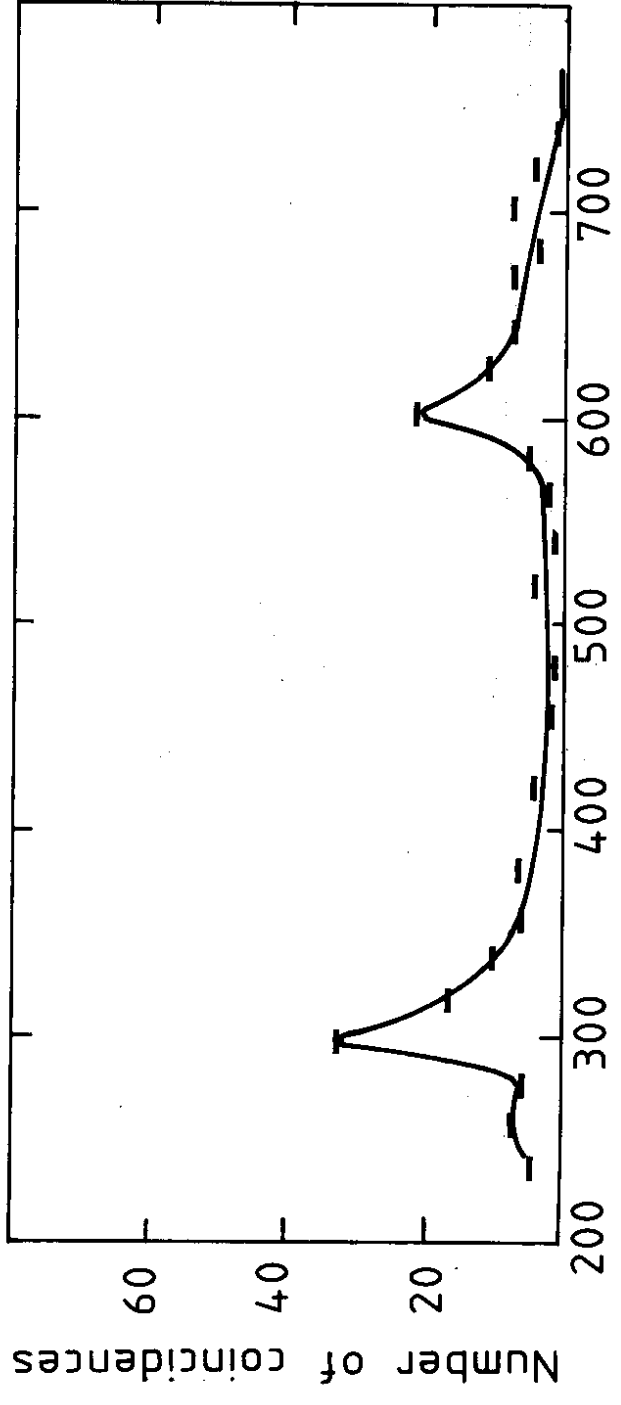
- | | |
|--|---------------------------------------|
| (1) Ar + CH ₄ (10%) + TMAE; | (3) He + CH ₄ (2%) + TMAE; |
| (2) Ne + CH ₄ (10%) + TMAE; | (4) He + CH ₄ (5%) + TMAE. |

Fig. 8 Intensity of the OH⁻ band as a function of the EF temperature.

Fig. 9 The light-to-charge ratio as a function of water-vapour partial pressure for Ar + EF vapour at 60 °C and a gas gain of 100.

Fig. 10 Energy resolution (1, 2) and gas gain (3, 4) as a function of applied voltage for a gap of 1 cm (1, 3) and 2 cm (2, 4) and Ar + TEA (70 Torr).

- Fig. 11 a) Behaviour of the cross-sections of excitation σ^* and ionization σ^+ when the kinetic energy of the electron is near E^* .
- b) Typical cross-sections of excitation σ^* and ionization σ^+ for noble gases.
- c) Behaviour of the cross-sections of excitation σ^* and ionization σ^+ for impurities and for the main constituent of the mixtures when the kinetic energy of the electron is near E_{basic}^* .



λ = Wavelength (nm)

Fig. 1

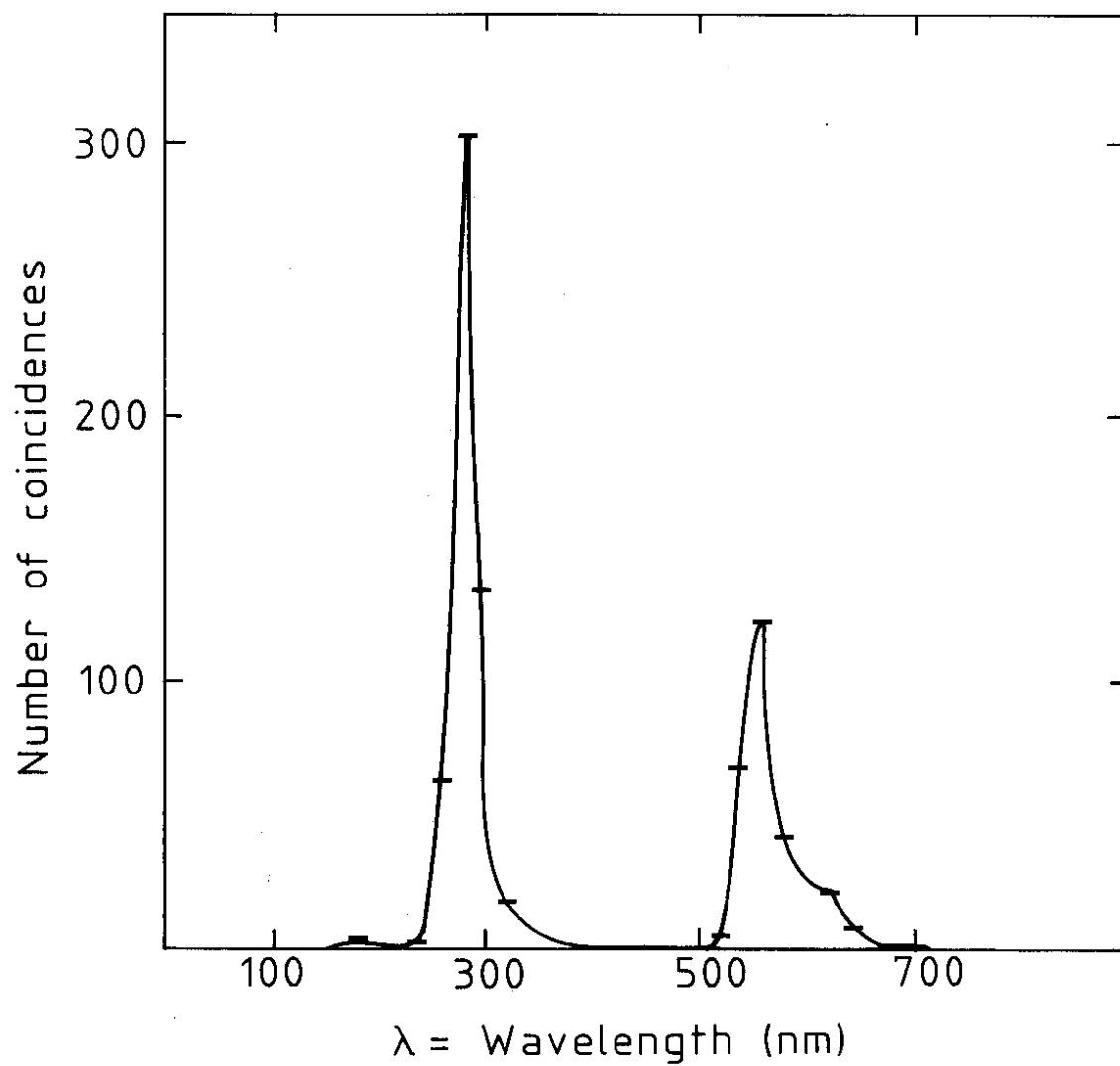


Fig. 2

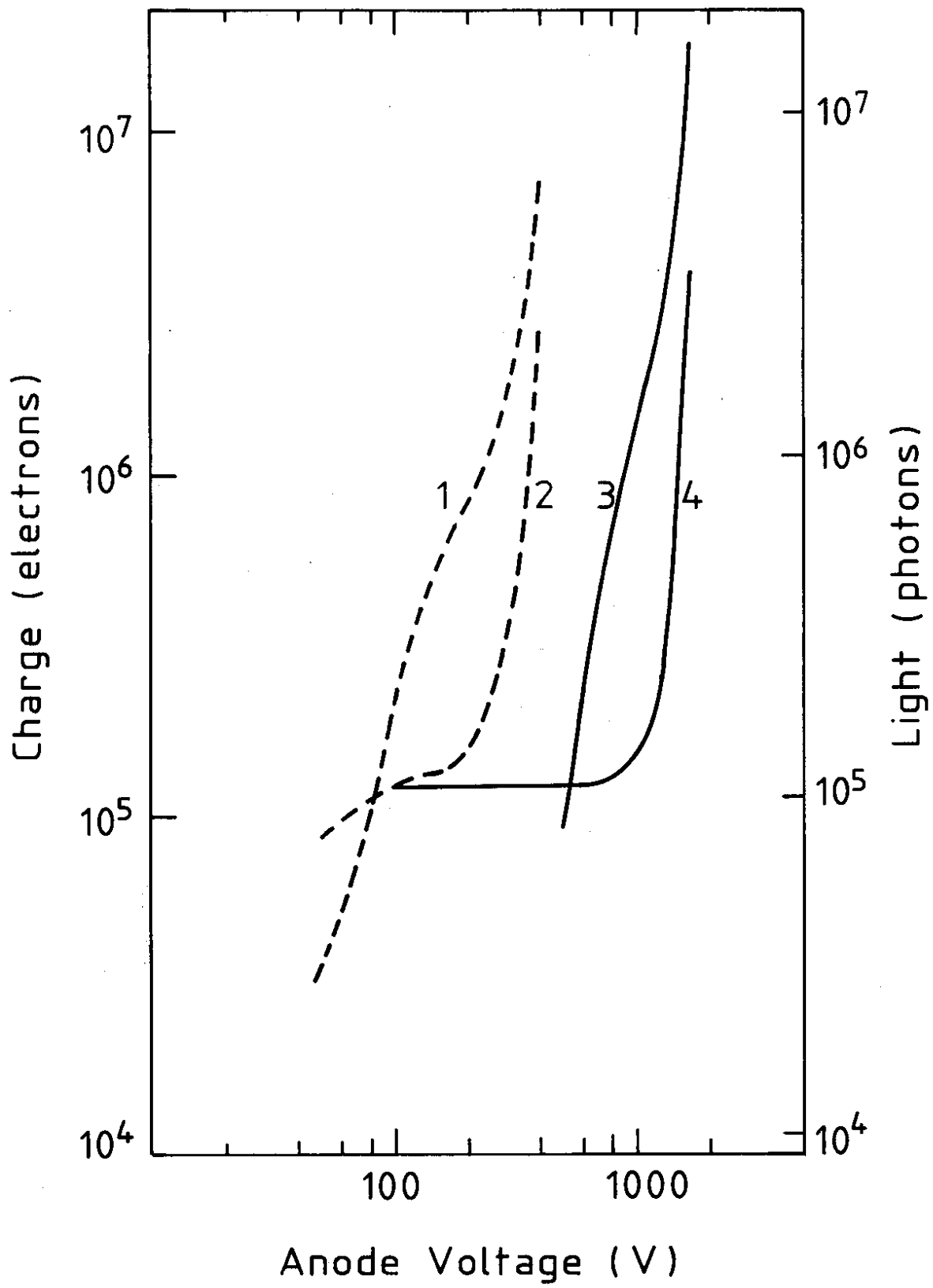


Fig. 3 a)

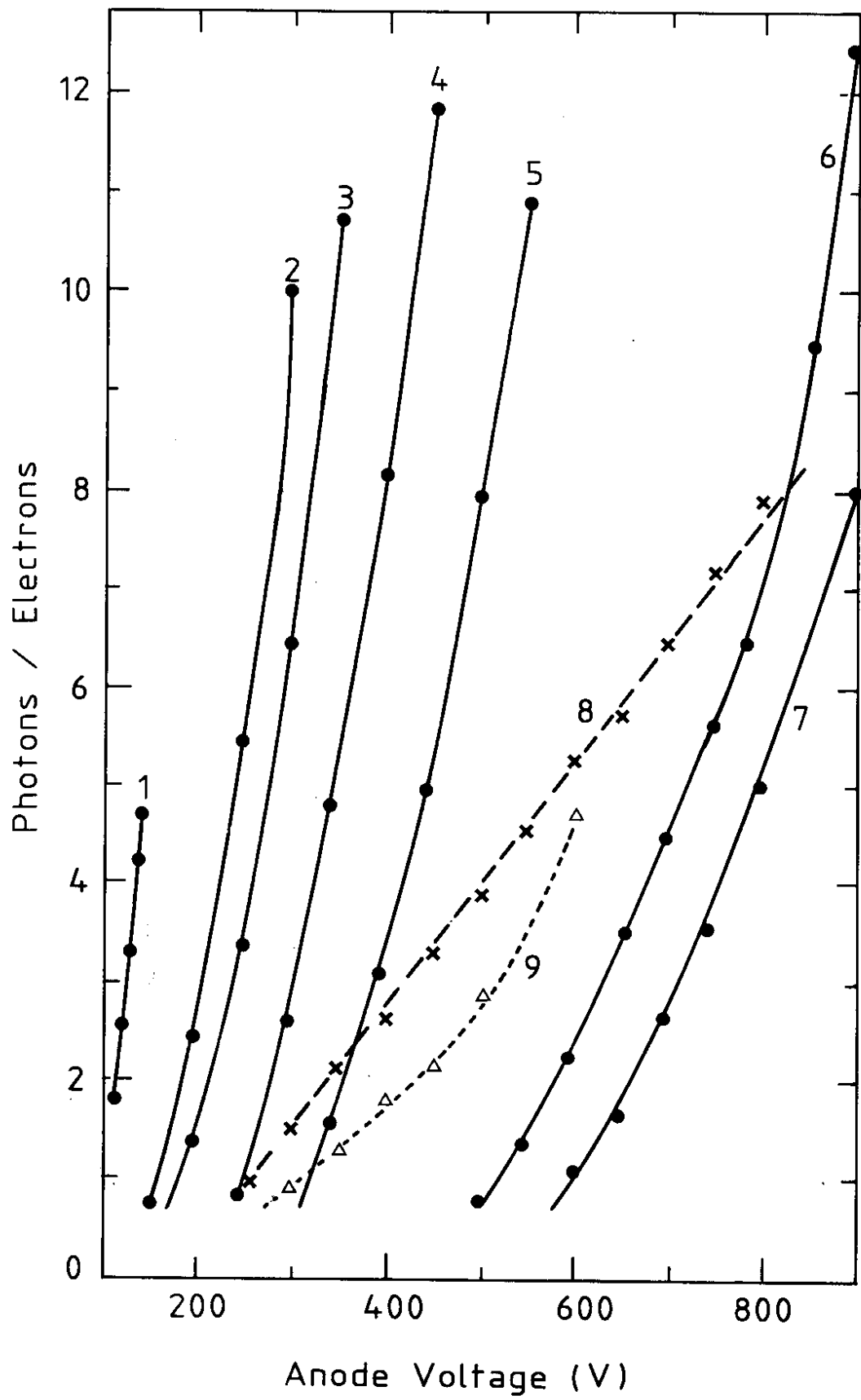


Fig. 3 b)

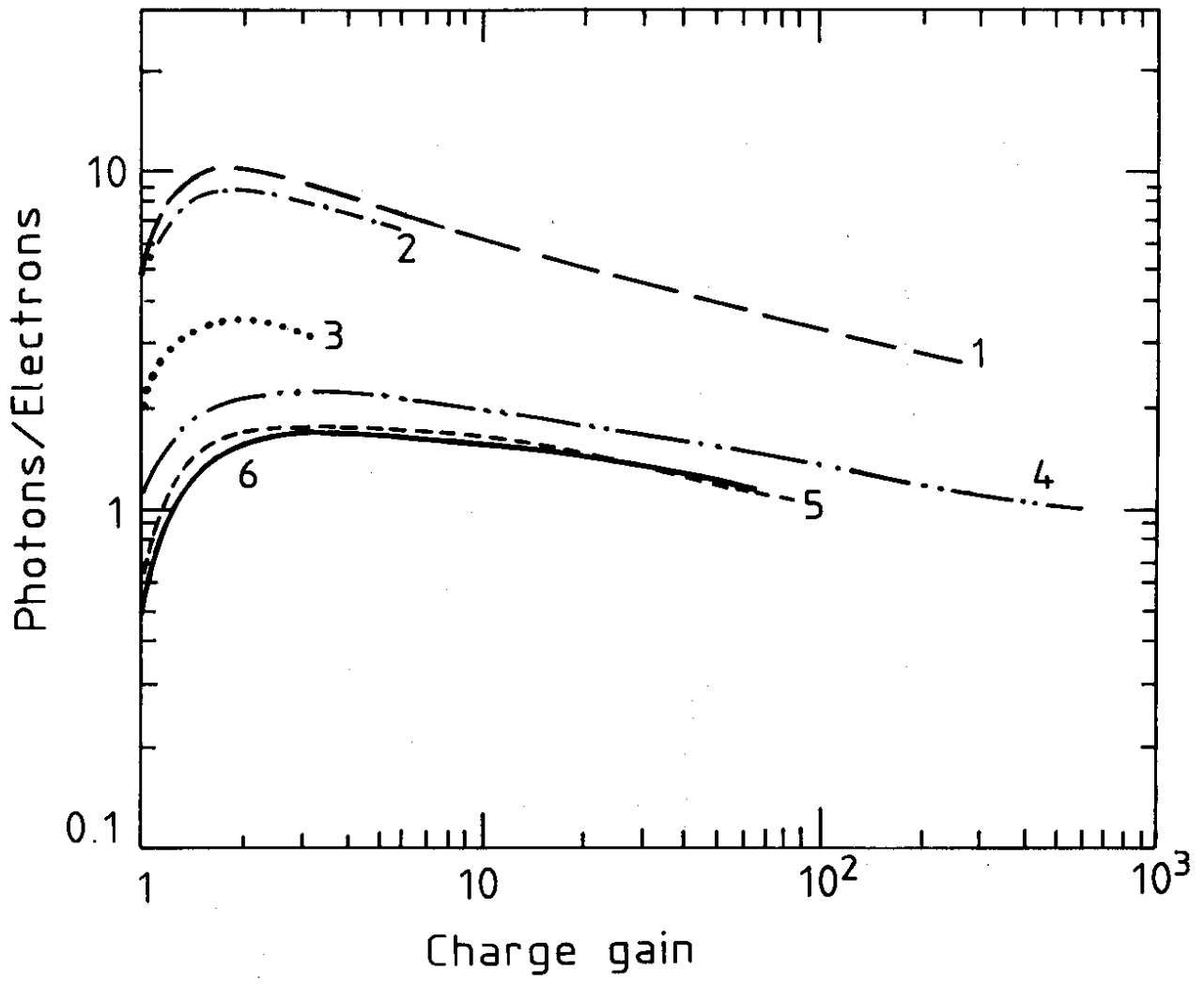
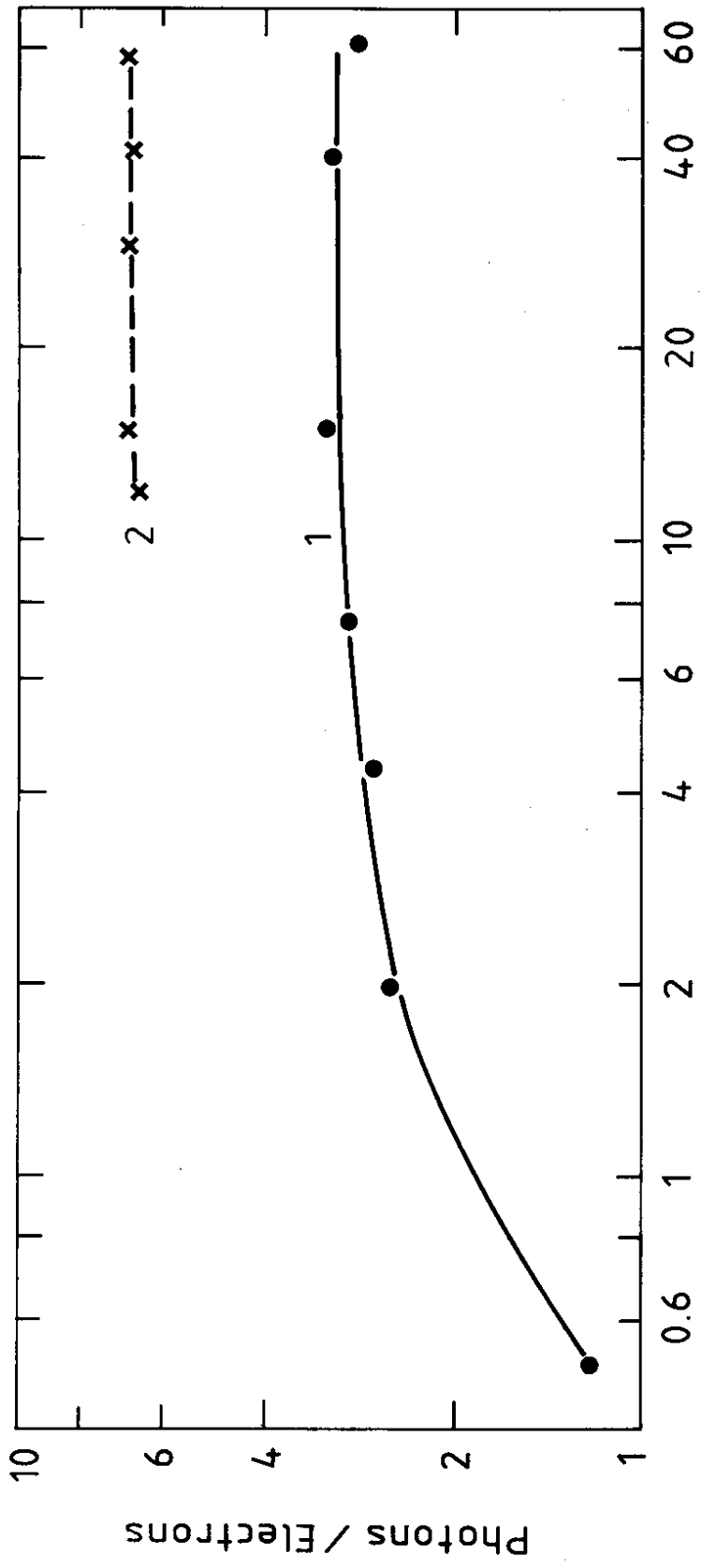
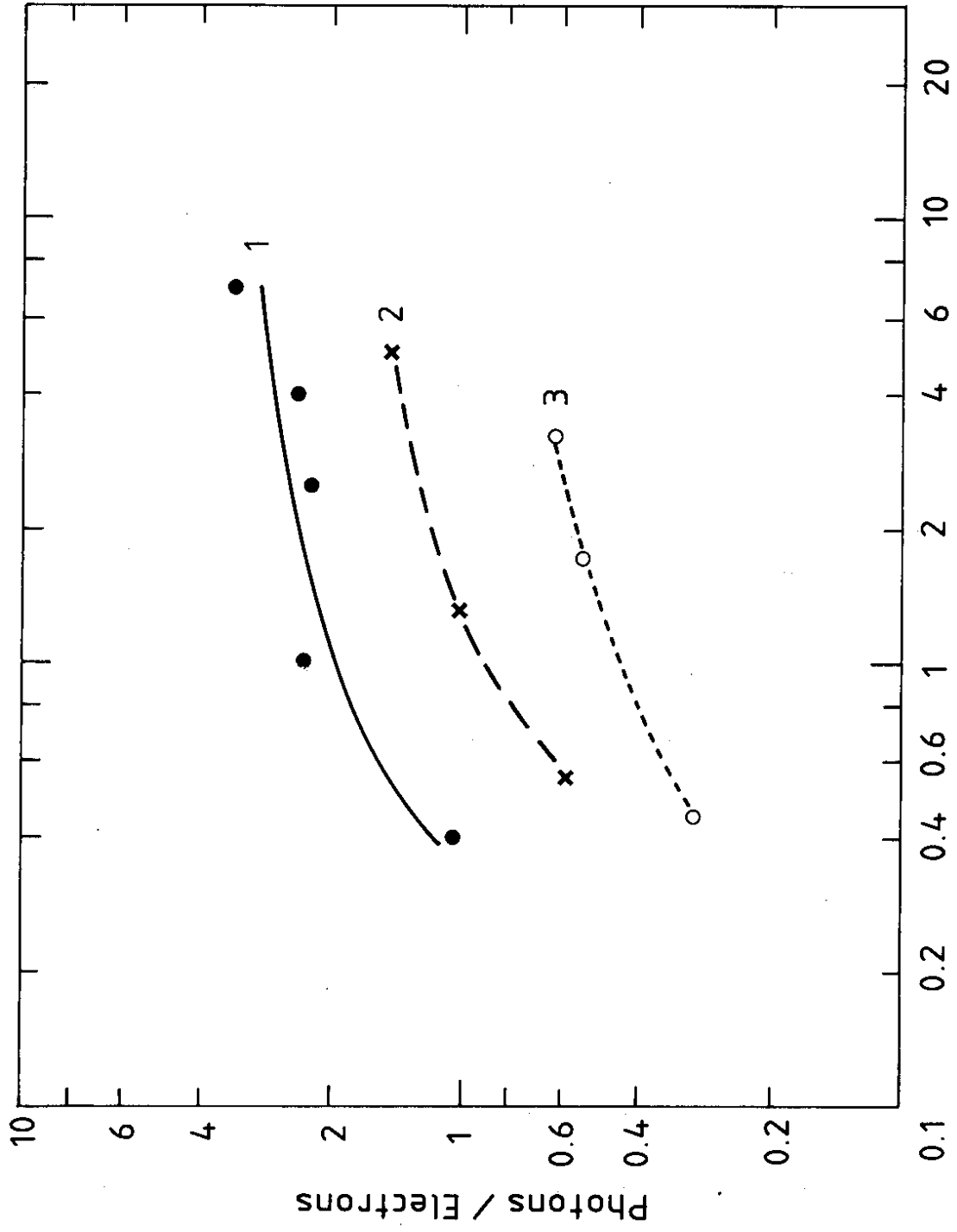


Fig. 4



PTEA (Torr)

Fig. 5



PTMAE (Torr)

Fig. 6

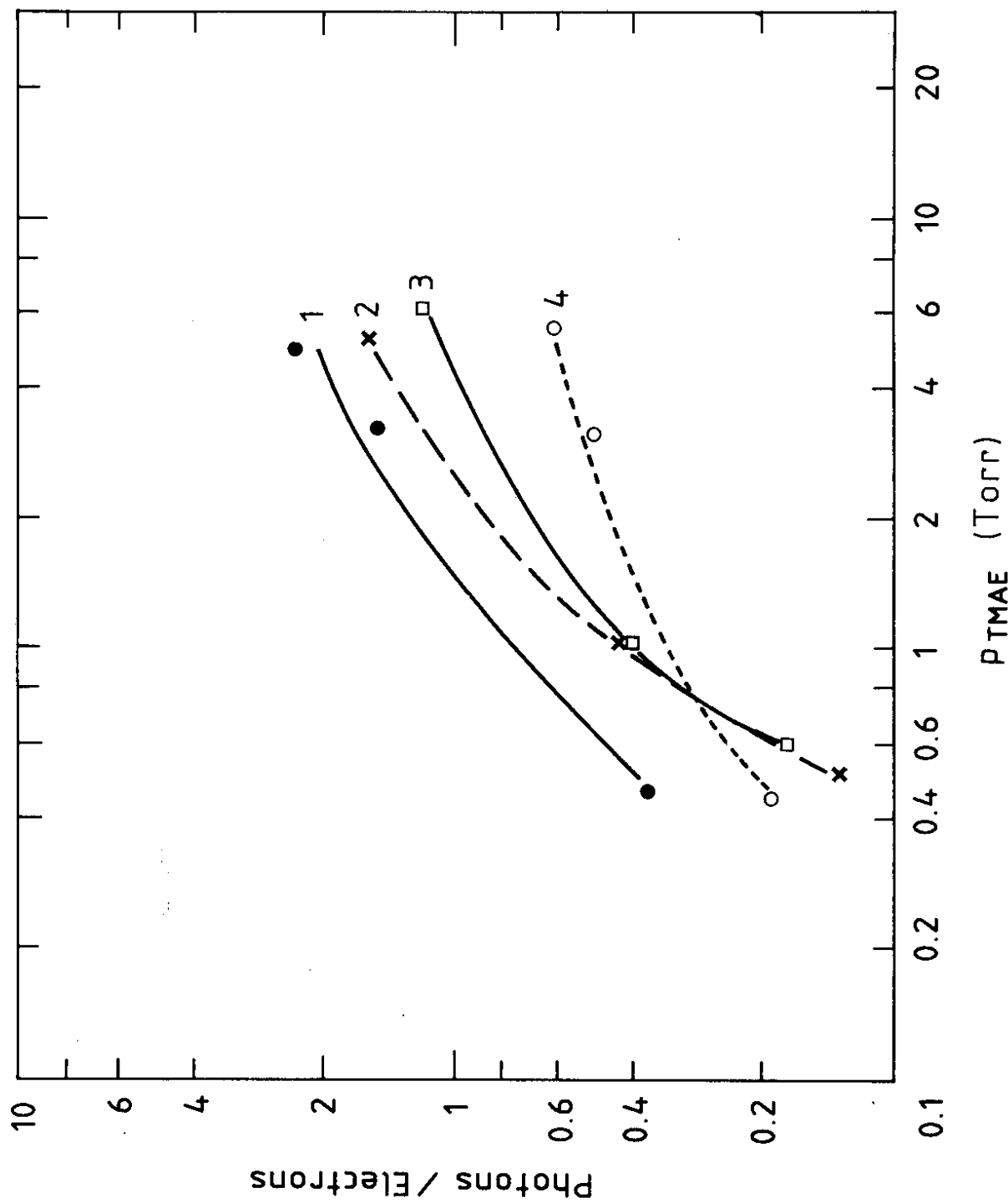


Fig. 7

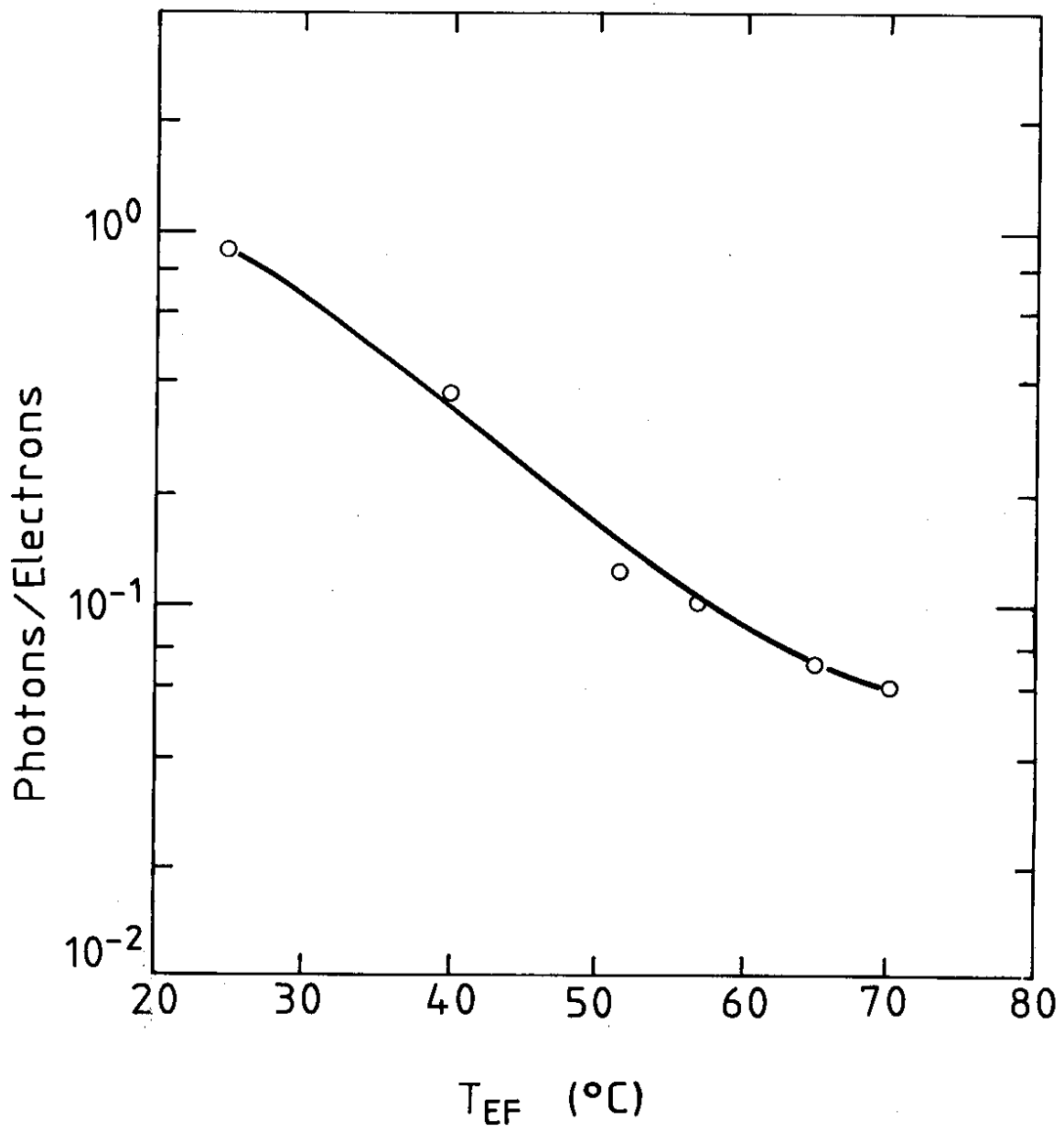


Fig. 8

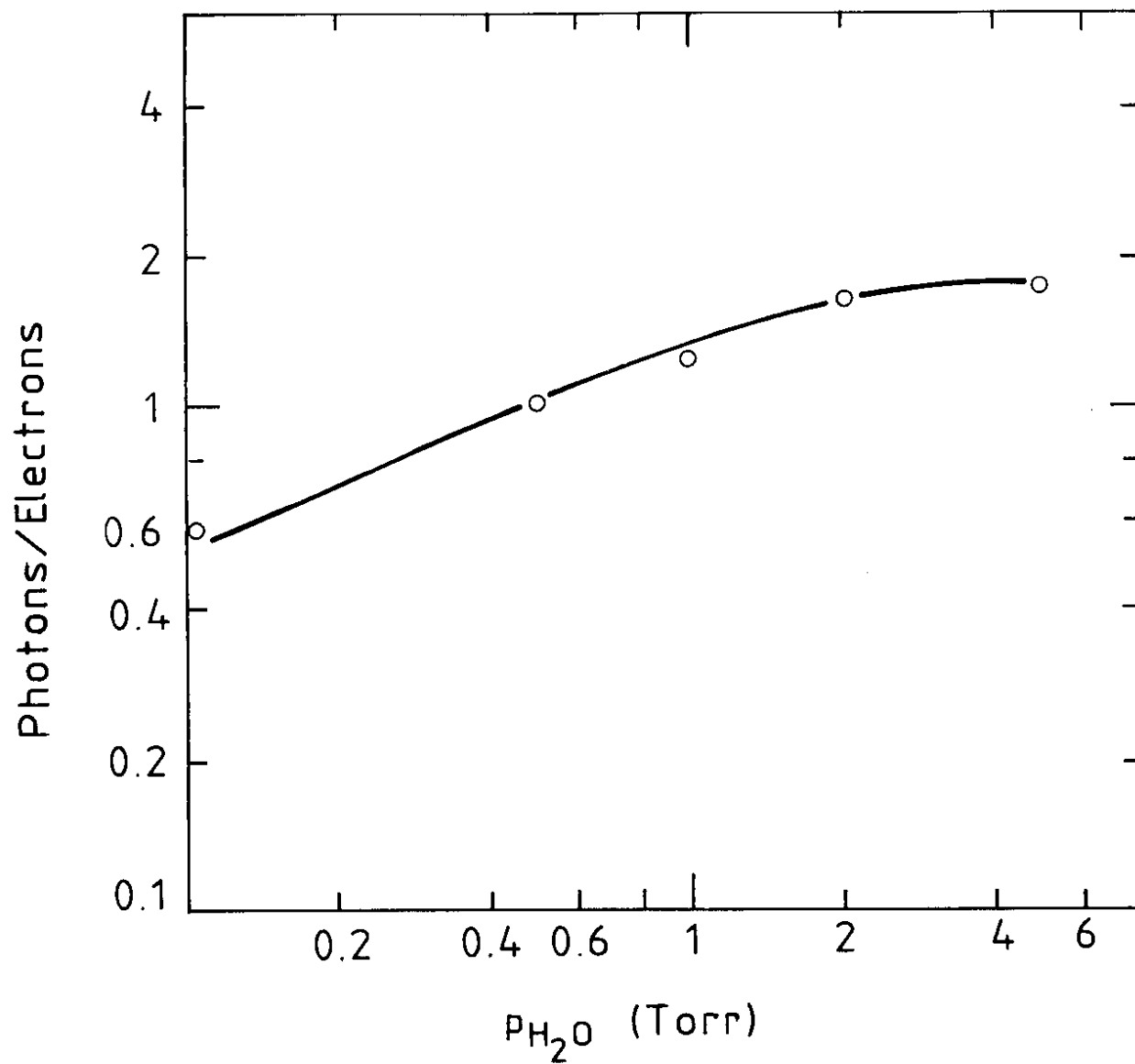


Fig. 9

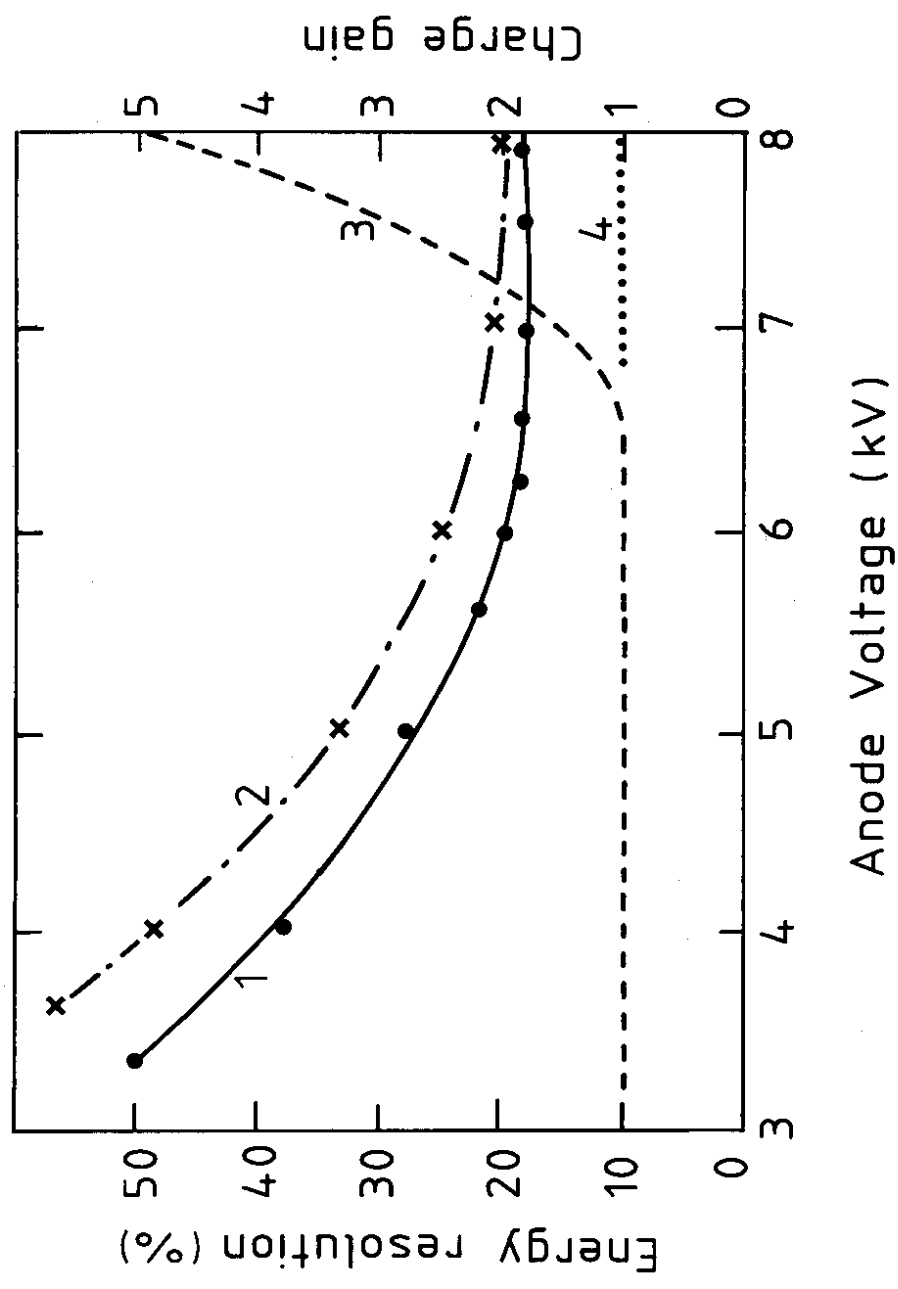


Fig. 10

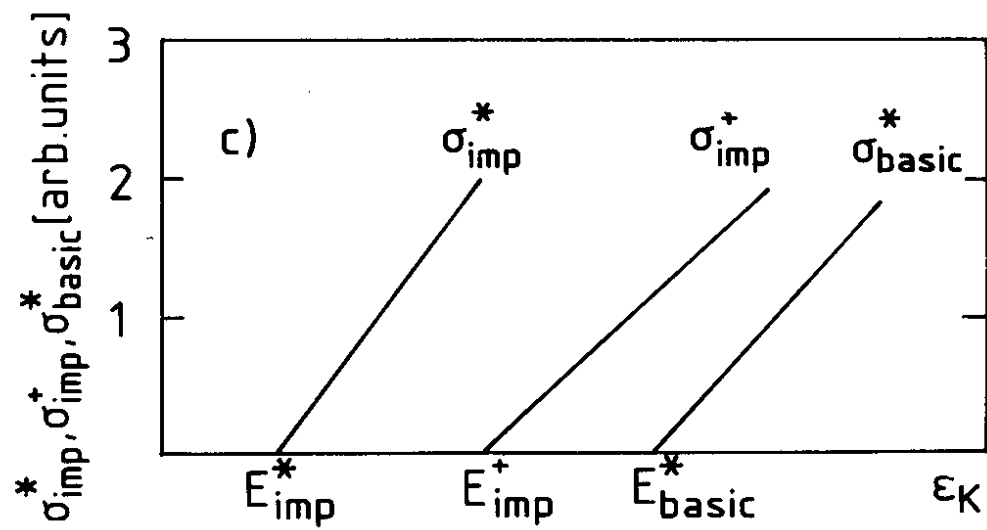
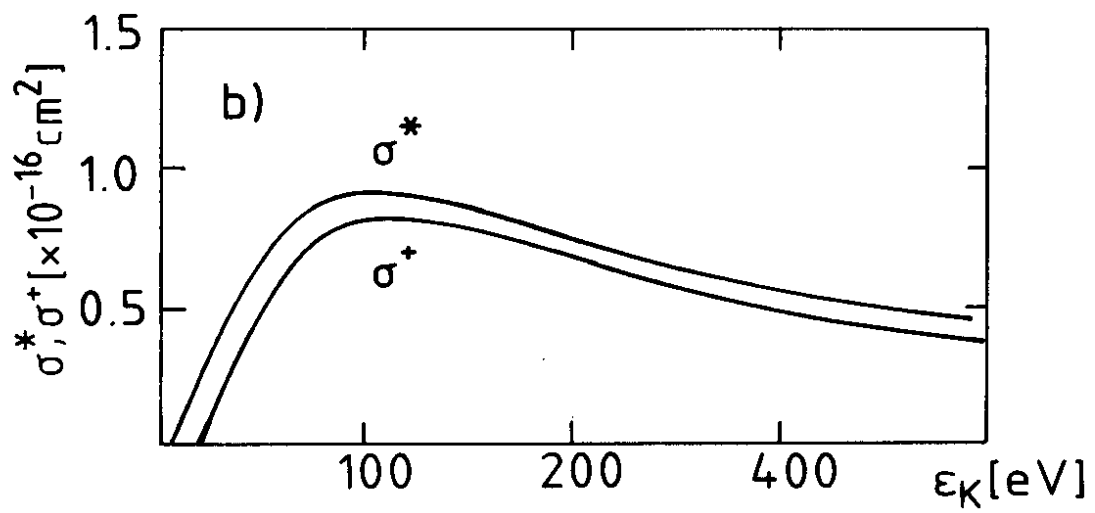
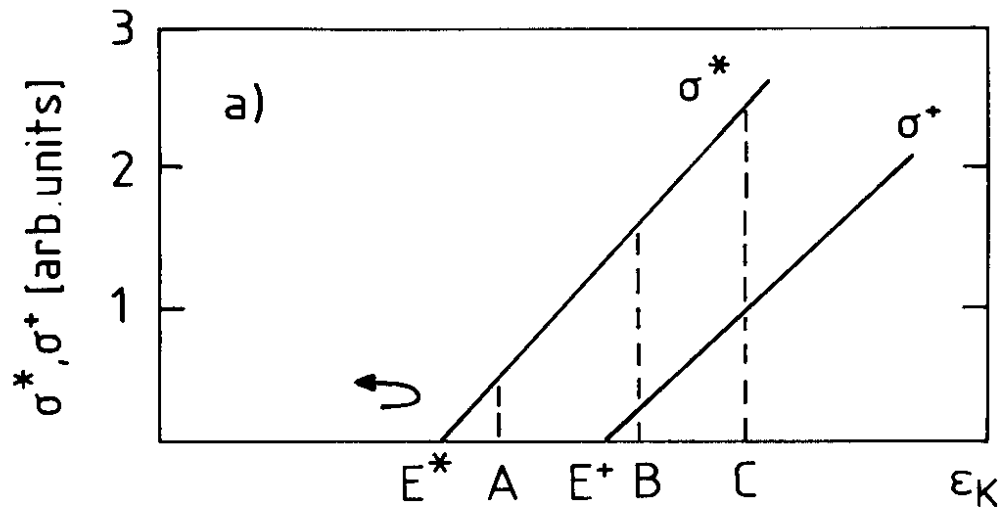


Fig. 11