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FUNDAMENTAL PROCESSES IN DRIFT CHAMBERS

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ABSTRACT

We review the history of electrons generated in the gas of drift chambers: primary ionization processes by charged particles or by neutral beams (X-rays, UV lasers); extraction of secondary electrons; transport and diffusion in an electric field and a magnetic field; scintillation and electron multiplication.

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1. INTRODUCTION

At this conference, devoted to the instrumentation for LEP, it has been thought worth while to recall the basic physical explanations for the various processes at work in a drift chamber. This subject has been reviewed several times in the last few years [1-3]. Instead of entering into many details, I will concentrate on a few items which could be important for instrumentation at LEP.

Of course in my selection I have been guided by a specific image of detectors, which are quite conventional and fall into the class of projection or imaging drift chambers [4]. Electrons are produced along charged particle trajectories (Fig. 1). They are then transported in a drift region towards a detecting cell where they are observed. A bidimensional detection in the cell together with the measurement of drift time allows the reconstruction in space of the creation point of the original electron. Pulse-height information is recorded and allows the measurement of initial ionization.

In such a scheme, which may well be superseded by others at the time of LEP operation, the main questions are the following:

- i) What amount of information is deposited by the charged particle (spatial information, dE/dx)? This represents the inherent limits of the method. Can we simulate for calibration purposes the energy deposition with photon beams?
- ii) How much is the information degraded in the drift region (diffusion, stability of transport coefficients, effect of magnetic field, etc.)?
- iii) What are the effects of the mechanisms chosen in the detecting cell?

This talk is therefore divided into three parts: extraction of electrons; the drift space; the detecting cell.

The three questions outlined above are also discussed in many other talks at this conference [4-8]. My own task is mainly pedagogical and will attempt to describe the fundamental processes at work from an atomic physics point of view. An understanding of what is going on is not only gratifying for the mind; it may also be important in the choice of the methods or of the parameters for a detector.

* * *

It is clear that, in this review, most of the quoted results or explanations are not mine and I profited very much from the discussions I had with many colleagues. I would especially like to thank W. Allison, G. Charpak, B.A. Dolgoshein, C. Rubbia, F. Sauli and T. Ypsilantis from whom I have borrowed many of the ideas put forward in this talk.

2. EXTRACTION OF ELECTRONS IN GASES

2.1 Charged particles

We start our review with the basic processes involved in the creation of electron ion pairs by a charged particle. Two phases can be distinguished.

- i) The extraction of primary electrons. This has been extensively described at this conference by Allison [5], and we will attempt to summarize only the main aspects of the understanding achieved so far.
- ii) The thermalization of these primary electrons which cool down and create secondary electrons.

2.1.1 Extraction. In a medium of low density the extraction of electrons by a particle of velocity βc is due to the exchange of a photon as symbolized in Fig. 2a. If the energy and momentum transfers are E and p , the cross-section for extraction of an electron is

$$\frac{d\sigma}{dE} = \int_{E/\beta c}^{\infty} dp f(p, E) \left(\frac{1}{E^2 - p^2 c^2} \right)^2 \sigma_Y(E, p) ,$$

where we have put in evidence the propagator of the virtual photon and the cross-section of this virtual photon on the atom; $f(p, E)$ describes the first vertex and contains kinematical factors. The mean energy loss is

$$\left\langle \frac{dE}{dx} \right\rangle \propto \int_0^{E_{\max}} E \frac{d\sigma}{dE} dE .$$

The relativistic rise comes from the fact that the kinematic limit of p comes closer to the pole of the propagator as β increases to 1. In other words, the range of the virtual photon increases with the velocity of the incident particle, and the cross-section increases indefinitely. Note that the upper limit of the integration for dE/dx increases also. However, in gaseous drift chambers the range of electrons extracted close to the kinematical limit $E_{\max}$ is long and the full energy is not usually deposited in the detection volume. Therefore this effect is not effective in the relativistic rise observed in gaseous detectors.

However, if the density of the medium is not infinitesimally small, a second contribution has to be included, namely the coherent scattering of the virtual photon on the electrons of the medium (Fig. 2b). This process can be described by an effective index $\epsilon(p, E)$ which is itself related to $\sigma_Y(p, E)$ (Fig. 2c). This is equivalent to saying that the real photon does

not propagate in the medium at the velocity of light. If $\epsilon(p, E) > 1$ this can be described by giving the photon a mass

$$m = E \sqrt{1 - \epsilon}.$$

Therefore the propagator is modified and

$$\frac{d\sigma}{dE} = \int_{E/\beta c}^{\infty} dp f(p, E) \left(\frac{1}{E^2 - p^2 c^2 - E^2 (1 - \epsilon)} \right)^2 \sigma_Y(p, E)$$

which no longer goes to infinity for $\beta = 1$. There is saturation of the relativistic rise corresponding to the limitation of the range of the virtual photon due to screening effects.

In order to make a computation, there is still $\sigma(p, E)$ to be calculated. Allison and Cobb in the photoabsorption ionization model [9] propose to take $\sigma_Y(p, E)$ to be equal to the photoabsorption cross-section for real photons $\sigma_Y(E)$ in the resonance region where E is small, and to be equal to the Rutherford cross-section for large E where electrons are quasi-free. Together with a proper treatment of ϵ , this prescription allows computation of the cross-section $d\sigma/dE$ shown for argon, for instance, in Fig. 3, where the contribution of the various shells and of the Rutherford part can be identified. With this input they are able to describe very well both the relativistic rise and the Landau fluctuations as shown in Fig. 4. Altogether this theoretical effort appears to have achieved a major breakthrough in the understanding of the details of the energy loss in a thin medium.

Such a description shows the discrete nature, at the macroscopic level, of the energy deposited. For instance, in argon there are [9] about 30 electrons per centimetre extracted from the M-shell with a typical energy of 30 eV, about 1.5/cm from the L-shell with 400 eV, and 0.03/cm from the

K-shell with a typical energy of 4 keV. For practical devices this has two consequences:

- i) The loci of equal drift time from a wire in a drift chamber are curved (see Fig. 5 computed for the JADE detector [10]). Therefore electrons created along the track arrive at different times. Since the mean distance between primary electrons is 300 μm in argon, this results in fluctuations in the arrival times of the first electrons; these fluctuations become larger the bigger the angle of the track with respect to the trajectories of electrons.
- ii) For ionization measurement there is a lot more information contained in the pulse than the total energy deposited. If the primary electrons could be detected individually and their energy measured, a factor of three [9, 6] could be gained on the mass resolution through ionization measurement.

The theory can be used also as a guide line to optimize the choice of the gas and the pressure. We refer the interested reader to the review talk of Walenta [6] at this conference.

2.1.2 Thermalization. The subsequent thermalization of the primary electrons is understood in much less detail. Primary electrons are slowed down by inelastic collision through which they extract both photons and electrons, until they reach an equilibrium temperature with the electric field and begin to drift. It is usually assumed that the total number of electrons produced, n_T , is proportional to the energy deposited, ΔE :

$$n_T = \frac{\Delta E}{E_i},$$

where E_i is 26 eV for argon.

The fluctuation on this number is given by

$$\frac{\sqrt{\langle \delta n_T^2 \rangle}}{n_T} = \sqrt{\frac{F}{n_T}},$$

where F is the Fano factor [11]; for argon it is equal to 0.2. Therefore for n_T of the order of 100 electrons/cm, these fluctuations are completely negligible in front of the Landau fluctuations.

The range of the primary electrons is not very well studied, neither theoretically nor experimentally. On the other hand, it determines the ultimate resolution limit of a drift chamber since it is related to the width of the track. If one extrapolates from results obtained in solids for the practical range R of electrons with formula of the type [12],

$$R = 9.9 \times 10^6 (E/1 \text{ keV}) \text{ g/cm}^2,$$

one gets in argon 2 μm for the M-shell electrons, 20 μm for the L-shell electrons, and 200 μm for the K-shell electrons. However, this extrapolation is not on very firm grounds and measurements are completely lacking. The only one I personally know of, is the measurement of the range R of primary electrons in a xenon streamer chamber [13] where a value of 200 μm is obtained. This value is very large compared with the expected value of 20 μm (M-shell electrons in Xe) from the above range formula. This effect can be explained by the fact that in a pure noble gas below the excitation levels, electrons have a hard time trying to lose their energy through elastic collision. Therefore after a very rapid decrease of the mean energy to the lowest excitation energy level, electrons diffuse for a long time before becoming thermal and beginning to drift appreciably in the electric field [14]. This effect should be much smaller in mixtures with organic molecules.

2.2 Calibration of drift chambers with photon beams

After this rapid survey of basic processes, we turn to the possibility of calibrating drift chambers by ionizing the gas along straight lines with photon beams, which could be X-rays or UV laser beams. This could be extremely important especially with large systems where the accuracy is mainly limited by systematics [15].

2.2.1 Pulsed X-rays. One possibility would be to use pulsed X-rays, as proposed by Hoffmann and Rubbia [16]. In order to penetrate a large volume of gas, the energy has to be higher than 30 keV. At this energy, electrons are extracted by means of two processes:

- i) *photoelectric effect*: in an argon mixture, the electrons extracted in this way are useless since they have too large an energy and too long a range;
- ii) *Compton effect*: the energy of extracted electrons is a continuum between zero and $2(h\nu)^2/mc^2$, which is 10 keV for 50 keV X-rays. This is a little high compared to the energy of primary electrons extracted by charged particles. However, two effects are going in the right direction:
 - a) The high-energy electrons give rather flat distribution in space, while the low-energy electrons have a small range and give a peak in the observed distribution of drift distance. This "Jacobian peak" effect is seen in the preliminary results of Rijssenbeck [17]: with the X-ray spectrum of Fig. 6a, he obtains the drift distance spectrum of Fig. 6b. Note that the tails are not symmetric because he was using too big intensities and single-hit time-to-digital converters (TDCs).

b) The magnetic field can curl high-energy electrons and clean up the tails (as shown in Fig. 6c at 7 kG). In this particular experiment the X-ray pulse width was limiting the resolution.

Calibration with X-rays has the nice advantage that diffraction is negligible. It can therefore be used to align devices over long distances. It does not require any special entrance windows in the usual detectors.

On the other hand, the ionization pattern produced is very different from that of a charged particle. In order not to be saturated by the dominant photoelectric effect and large pulse height, a low enough intensity has to be used, extracting one useful Compton electron every two or three cells. This Compton electron gives rise, by thermalization, to a blob of electrons which have properties that are very different from those of the electrons spread along a charged track. They all arrive on the sense wire at the same time. Therefore from pulse to pulse, their measured drift distance will fluctuate because they are not created along a locus of equal drift time to the wire (see Fig. 5). This can be contrasted with charged particle tracks where the closest primary electron is detected. Intrinsically the X-ray beam gives a wide distribution which has to be averaged over many pulses, and the averaged measured drift distance is different from the one of a real track in a way which is dependent on the shape of the loci of equal drift time from the wire and on the magnetic field.

2.2.2 UV laser beams. A much closer simulation of a charged track can in principle be obtained with pulsed UV laser beams. The intensity can be adjusted in order to create, by photoionization, one electron every 100 μm on the average.

Direct photoionization could be attempted [18]. Adding a low ionization potential impurity C to the gas, the process

could be used. However with an ionization potential around 7 eV, which is about the lowest that can be obtained with an organic substance, wavelengths as short as 170 nm have to be used, and such vacuum UV beams are difficult to handle.

More promising is the use of double photon absorption which allows one to work in the close UV region at a wavelength that is twice as large (340 nm). The basic process is shown schematically in Fig. 7a. A first electron excites the molecule to a usually virtual state. This virtual state lives for a time $\tau \sim 10^{-16}$ s. If a second photon arrives during that time, it can ionize the virtual state. The ionization rate is, of course, quadratic with respect to the flux. When the intermediate states exist (Fig. 7b) cross-sections are much larger, and one speaks of double-step processes. If the first transition is saturated, the ionization rate is expected to be linear with respect to the flux.

- i) Double photon absorption has been observed by Bourotte and Sadoulet [18]. By adding a small proportion (10^{-5}) of diethylaniline in the gas (ionization potential = 7 eV) they observed, with a N₂ laser ($h\nu = 3.7$ eV), 500 electrons/cm with an energy of 100 μ J and an area of 1 mm². Figure 8a shows the pulse observed on seven wires when the beam is parallel to the sense wire plane, and Fig. 8b when the beam is parallel to the drift electric field. The observed dependence is quadratic, as shown in Fig. 9, and the cross-section estimate is of the right order of magnitude.
- ii) Although it is more difficult to prove unambiguously, a double-step process is probably responsible for the ionization by close UV beams observed by three groups.

Anderhub, Devereux and Seiler [9] have observed ionization with a N_2 laser and the addition of some nickelocene $[Ni(C_2H_5)_2]$. This organo-metallic substance has a broad absorption maximum around 337 nm and an ionization potential of 6.5 eV.

More surprising are the results obtained by two groups, Bourotte and Sadoulet [18] and H. Hilke [20], with lasers at 265 nm and 337 nm, respectively. They observed ionization of the gas without specifically adding any impurity to the commercial gases (argon, isobutane, propane, or ethane). Moreover, the number of electrons is proportional to the intensity (Fig. 10). The most likely explanation [18] is that the beam ionizes, by a double-step process, a complex molecule (e.g. pump oil) with low ionization potential and a broad absorption maximum around 300 nm. Clearly, more experimental study is needed before the phenomenon can be understood.

Whatever the basic mechanism used, calibration with laser beams has the advantage of simulating very closely ion-electron pair creation by charged particles. The two differences are that electrons are not emitted in clusters but more uniformly, and that there is no Landau fluctuation (see Fig. 8c). In principle, one pulse is sufficient to calibrate a system, thus allowing a detailed monitoring of fluctuating distortions (e.g. space charge). Moreover this good simulation of a track by a UV laser beam makes it also potentially useful for understanding fundamental properties of drift chamber systems and of the associated electronics: relative normalization of pulse-height, cross-talk, two-particle separation, electric field shaping, angular behaviour, space charge problems, etc.

The obvious drawback -- in addition to the need for UV transparent windows -- is the diffraction which limits the effective track length to about

2 m [18]. UV laser beams are therefore not well adapted to the relative positioning of many devices, and in this respect the pulsed X-ray method appears complementary.

3. THE DRIFT SPACE

3.1 Basic processes

When the primary electrons have lost most of their energy through ionization and excitation, they begin to be sensitive to the electric field and to drift.

Let us first see what happens in the absence of magnetic field [1]. Electrons make a random walk between the molecules. They are accelerated between successive collisions in which they lose part of their energy and their initial direction. They can be described by the distribution $F(v, \cos \theta)$ of their random velocity v and their angle θ with the electric field. The drift velocity w_L is then

$$w_L = \int v \cos \theta F(v, \cos \theta) dv d \cos \theta ,$$

and the mobility is $\mu = w_L/E$.

The diffusion coefficient D , defined by

$$\vec{\nabla} \rho = -\frac{1}{D} \rho \vec{v} ,$$

is

$$D = \int \frac{\ell v}{3} F(v, \cos \theta) ,$$

where ℓ is the mean free path. One also introduces the characteristic energy $\epsilon_k = eD/\mu$, which is related to the average energy of electrons. It can be shown [1] to be bounded from below by kT .

In fact for bunched electrons there are two different coefficients D_L and D_T in the directions parallel and perpendicular to the electric field [21]. This effect comes from the fact that the distribution $F(v, \cos \theta)$ depends on the position in the bunch. Electrons which have diffused to the leading edge are on the average more energetic, since the work of electric field has been bigger and therefore they are less sensitive to this field. Therefore their drift velocity is smaller and there is a rebunching effect. Therefore quite generally

$$D_L \leq D_T .$$

In practice, these two quantities are rarely measured in the gases used in drift chambers. Figure 11 shows the measurement by the JADE [10] group of their gas: argon + methane + isobutane (0.887 : 0.085 : 0.028).

When there is a magnetic field, electrons are not only accelerated by the electric field but are also deflected by the magnetic field. This has three effects.

- i) If the magnetic field is perpendicular to the electric field, electrons drift at an angle α_D with respect to the electric field. In other words, in addition to the component w_L parallel to the electric field, the drift velocity has a component w_T along $E \times B$ such that

$$\operatorname{tg} \alpha_D = \frac{w_T}{w_L} ,$$

often written as

$$\operatorname{tg} \alpha_D = w_M \frac{B}{E} ,$$

where w_M is the "magnetic drift velocity".

- ii) If the magnetic field is parallel to the electric field, the transverse diffusion is decreased because the electrons have a tendency to curl in between collisions. It is multiplied approximately by the factor

$$\frac{1}{1 + \frac{3}{2} \frac{B^2}{E^2} w_L^2}$$

which is usually quite close to 1.

- iii) In the case of a magnetic field perpendicular to the electric field w_L decreases in the same proportion, for the same reason. However, since w_T is not too far from

$$\sqrt{\frac{3}{2}} \frac{B}{E} w_L, \quad (\text{i.e. } w_M \sim \sqrt{\frac{3}{2}} w_L)$$

the drift velocity w along the electron trajectory,

$$w = \sqrt{w_L^2 + w_T^2},$$

is not greatly affected.

The theory of these phenomena is very well understood [1, 22]. From elastic and inelastic cross-sections one can compute the velocity distribution (see Fig. 12 for argon) and all transport coefficients. Unfortunately σ_{inel} is not well known for the hydrocarbons, and the only possibility is to adjust them in order to fit the experimental behaviour at various concentrations. From these studies, transport coefficients other than those used as input can be extracted, such as the diffusion of the electron cloud σ_x after a unit drift distance x :

$$\sigma_x = \sqrt{\frac{2Dx}{w}} = \sqrt{\frac{2e\epsilon_k x}{eE}}.$$

(see Fig. 13).

Quite independently of these detailed calculations, it is easy to see that the velocity distribution $F(v, \cos \theta)$ is a function of the electric field E and the pressure P through the ratio E/P . It then results that

- i) w_L and w_n are functions of E/P ;
- ii) PD , Pw_T , $P \lg \alpha_D$ are functions of $f(E/P)$.

3.2 Interesting properties for drift chambers

After this brief reminder of the physics involved, we now turn to applications to drift chambers.

3.2.1 Saturated drift velocity. It is extremely important for the stable operation of a drift chamber that the drift velocity is saturated. In fact it is naturally saturated around an E/P of 1 kV/(cm atm) for mixtures of argon and hydrocarbons. This is linked to the maximum energy of important vibration levels [1].

Groups working at high pressure but at relatively low E/P in order to have reasonable drift voltages, had to find mixtures which give saturated drift velocity at low E/P . Figure 14a gives the drift velocity obtained by the JADE group with its mixture of argon (87.2) + CH_4 (10%) + isobutane (2.8%) at $E/P \sim 0.23$. Figure 14b summarizes the results obtained by Dodokhov and co-workers [23] at 100 atm. By adding methane (0.2%) to the original mixture of argon (99.3%) and xenon (0.5%), the drift velocity is increased and is saturated at $E/P \sim 0.015$.

3.2.2 Low diffusion. In drift chambers, diffusion has clearly to be minimized since it is the prime factor entering in the resolution. In discussing these matters, however, care should be taken to distinguish between the r.m.s. dispersion σ_x of the electron cloud and the r.m.s. dispersion σ of the drift distance. The first is a characteristic of the gas and is equal after a drift distance x :

$$\sigma_x = \sqrt{\frac{2Dx}{w}} = \sqrt{\frac{2\varepsilon_k x}{E}} .$$

On the other hand, σ depends on the detection method. In a system that is sensitive to the first electron,

$$\sigma = \frac{1.28 \sigma_x}{\sqrt{2 \log n}} ,$$

where n is the number of electrons in the cloud. However, if the centre of gravity is detected,

$$\sigma = \frac{\sigma_x}{\sqrt{n}} .$$

In practice, with the standard way of detecting electrons by multiplication and measuring the time of flight of the electric pulse over threshold, σ is between the two extreme values,

$$\sigma \sim \frac{\sigma_x}{2} - \frac{\sigma_x}{3} .$$

Typical values are :

$$\begin{aligned} \varepsilon_k &\sim 0.1 \text{ eV} , \\ \sigma_x &\sim 150 \text{ } \mu\text{m}/\text{cm}^{\frac{1}{2}} , \\ \sigma &\sim 50-75 \text{ } \mu\text{m}/\text{cm}^{\frac{1}{2}} . \end{aligned}$$

In order to improve σ , three methods can be tried.

- i) To work on the detection method in order to measure the centre of gravity of the electron cloud. To my knowledge, with detection by electron multiplication, nobody has obtained significant improvement by using the zero crossing technique. This is presumably because in a drift chamber the primary electrons are not created at equal drift times from the wire. In addition, the $1/t$ shape of the pulse and the space charge created by the first arrived electrons modify the weight

of the various electrons in the pulse. However, the advent of fast analog-to-digital converters (flash ADCs) may allow significant progress along these lines. Detection by scintillation may also allow the shape of the electron cloud to be measured directly.

- ii) To make a proper choice of gas in order to decrease the temperature of electrons in the gas. However, it cannot decrease below the ambient temperature. One can show (in theories which do not take into account the difference between D_T and D_L) that

$$\epsilon_k \geq kT .$$

If the lower limit is reached,

$$\sigma_x = 70 \mu\text{m}/\text{cm}^{\frac{1}{2}} \quad \text{at} \quad 1 \text{ kV}/\text{cm} ,$$

which represents a gain of 2 with respect to the usual case. But the distribution of electrons is Maxwellian and, as in the case of positive ions, the mobility is constant and the drift velocity is proportional to the electric field.

- iii) A third possibility is to increase the pressure P and maintain the ratio E/P . In this case σ_x is proportional to $1/\sqrt{P}$.

In practice E/P is reduced, but since the behaviour σ_x varies slowly with E/P in the region of interest (Fig. 13), nearly the full gain is achieved.

This method is being used by several groups: JADE, Mark II (Fig. 15a), Baskakov et al. [24] and Alikhanian et al. [24] (Fig. 15b). Using scintillation at 300 atm in an argon (99%) + N_2 (1%) mixture, the latter group (Ref. 24) has recently [14] succeeded in measuring a dispersion of the electron cloud σ_x :

$$\sigma_x = 10-15 \text{ } \mu\text{m}/\text{cm}^{\frac{1}{2}},$$

which could allow a significantly better resolution σ on the measured drift distance.

Limits are encountered, however. Without speaking of multiple scattering in the wall of the pressure vessel, high pressure makes detection more difficult. Whether scintillation or electron multiplication is employed (see Sections 4.2.1 and 4.2.4), only a very small proportion of quenching molecules can be added to the noble gas used, and the electron temperature is much higher than in the usual mixtures (by as much as a factor of 5, see Fig. 13).

3.2.3 Low drift angles. A final comment could be made regarding the drift angle in a magnetic field. It is a nuisance both because it limits the magnetic field in projection chambers with the magnetic field transverse to electric field, and because it makes electron trajectories sensitive to the space-charge effects of positive ions even in the case of a uniform distribution. Defining w_M as

$$\text{tg } \alpha_D = w_M \frac{E \cdot B}{E^2},$$

w_M can be shown theoretically to be of the same order of magnitude as w , the exact ratio depending on the velocity distribution of electrons. Experimentally, as can be deduced from Breskin et al. [25] and Daum et al. [26] around 1 tesla w_M is equal to 1.5-2 w_L , where w_L is the drift velocity along the path of electrons, and taking w_M/w as a constant is a very rough approximation.

This point has not been studied very much, neither experimentally nor theoretically. Presumably a lot can be gained from the proper choice of

the gas since -- at least to my knowledge -- no lower bound exists for w_M , and work along these lines may be important for PEP detectors.

4. THE DETECTING CELL

We now come to the cell in which the electrons are detected. Unless there was initially a high primary ionization of more than some 10^4 electrons, the signal generated by electrons coming out of the drift region is too small to be detected by electronic means and has to be amplified.

Traditionally this is done directly in the chamber where the electrons are accelerated in a very high field region and are multiplied through collisions with the gas molecules. More recently it has been realized [7, 24, 27] that the scintillation light emitted by electrons in noble gases at medium field can be observed after wave-shifting through a photomultiplier. In this case the amplification occurs externally to the chamber. Clever schemes [28, 29] have been proposed for using these photons in order to couple two proportional chambers having different gas volumes.

4.1 Basic processes at high electric field

In order to understand the processes at work, we have to describe them in some detail.

4.1.1 Pure noble gas. Let us first consider the case of a pure noble gas.

At low field (< 2.5 kV/cm at 1 atm in argon), collisions of electrons with the gas are elastic, and the electrons just drift and diffuse in the electric field.

Above a certain threshold, the electron distribution is wide enough (see Fig. 12) to overlap the excitation level of the normal gas. The drift velocity increases sharply and more important excited atoms are

created. Some of these states have short lifetimes of a few nanoseconds and emit a resonance line,

which will diffuse slowly in the gas since it is also absorbed very easily by another atom. Other states, which we will call A^{**} , are metastable and decay only after 100 μ s or more. During this time they may collide with another atom to form a excimer,

which is a temporary molecule where the excited state is attractive whilst the ground state is dissociative. The diatomic excimer decays through the emission of a continuum of the Franck-Condon type (Fig. 16). This is thought to be the main origin of scintillation light observed in noble gases [3] (Fig. 17a).

If the field is pushed even higher (10^4 V/cm in argon at normal pressure), the electron distribution is wide enough for some of the electrons to be above the ionization threshold. They begin to extract other electrons according to the reaction

where the ion is usually in an excited state and can decay with the emission of a photon or can transfer excitation energy to another atom:

It is clear, therefore, that light is emitted in the ionization process, and one can imagine two multiplication regimes:

- i) the ejected electron is accelerated and can itself ionize another atom; this is the usual mechanism and the multiplication is electron mediated;
- ii) the emitted photons can have enough energy to ionize the gas; in the case where this is dominant, the multiplication is photon mediated.

Unfortunately it is extremely difficult to have stable electron multiplication in pure noble gases because of parasitic phenomena. These arise mainly from the interactions of photons, metastable states, or ions with the wall:

These phenomena can clearly occur energetically because of the low work function of usual metals. They produce a delayed positive feedback mechanism which may result in erratic behaviour of the chamber. This is usually cured by adding an organic gas which acts as a quenching agent.

4.1.2 Quenching mechanisms. The basis for the quenching mechanisms is that a molecule, especially if it is complex, has a lot of degrees of freedom and can absorb energy very efficiently.

At low electric field, even a small proportion of complex molecules in the gases reduces the temperature of electrons and consequently increases the drift velocity and decreases the diffusion.

This addition of complex molecules pushes the effective threshold for light emission to higher fields, and it can do this in two different ways.

- i) Good quenchers have a photoabsorption cross-section significantly bigger than the photoionization cross-section (see Fig. 17b). They can therefore catch photons emitted in the various de-excitation processes. There are many means by which these molecules can dissipate their energy (see, for example, Christophoron, Ref. 3) other than by radiation, e.g. internal transition, sharing of electronic excitation between many vibration modes, dissociation, etc.). Cross-sections for photo-absorption are typically of the order of 10^{-17} - 10^{-16} cm².
- ii) Similar mechanisms occur with excited states which can efficiently transfer their energy to a complex molecule,

with cross-sections of the order of 10^{-15} cm².

The same processes are operative in the multiplication region and usually stabilize the avalanches. However, because the ionization potential of the complex molecule is generally lower than that of noble gases, other effects can be present:

- i) The photoionization cross-section is not negligible and photons can ionize the molecule with quantum efficiency of typically 20%.
- ii) Electrons can ionize the complex molecule directly.
- iii) Collisions between high enough excited states of the noble gases and the additive may lead to ionization:

This is the Penning effect for which cross-sections may range from 10^{-16} to 10^{-15} cm².

iv) Finally, there may be ion exchange

with similar cross-sections. This may be annoying in the case where C^+ ions polymerize easily. This is cured by adding a few percent of another additive of lower ionization potential (typically methylal or isopropyl alcohol) which can cause another transfer

in, say, $1/(10^{-16} \times 2.67 \times 10^{19} \times 10^{-2}) = 0.03$ cm for 1% concentration.

4.2 New experimental results

The above enumeration of the possible mechanisms shows the complexity of the physics involved, and the absence of basic data on the cross-sections prevents any accurate predictions from being made. However, knowledge of the mechanisms may guide the clever experimenter to solve problems experienced in his applications. I would like to illustrate this statement by a few examples of recent progress.

4.2.1 Scintillation. Scintillation has been used by Dolgoshein and co-workers as a practical method of detection at high pressure where amplification is difficult (see subsection 3.2.3). However, early attempts with pure xenon at 20 atm [24] showed a relatively slow decay of the pulses (> 500 ns). They attributed these effects to excitation of metastable states and successfully solved the problem by adding 1.5% of N_2 which acts as a quencher. Presumably the reaction involved is

The light output is decreased by about 50%, but the pulse is nicely symmetric and is a direct image of initial distribution of electrons. With

this technique they have been able to measure the longitudinal diffusion of electrons in argon at 300 atm to be 10 to 15 μm [14]. Therefore both an extremely good accuracy ($\ll 10 \mu$) and two-particle resolution (30-50 μm) could be achieved.

In order to decrease multiple scattering, the same group have used helium at the same pressure. However, the scintillation light of He is peaked between 50 and 100 nm and would be extremely difficult to observe unless it is wave-shifted directly in the gas. This was achieved by adding 0.3% of Xe, which may act in two ways:

or

where now it is the xenon which scintillates. A small proportion of N_2 (0.06%) is added to quench metastable states as explained above.

In the same context we can note the coupling of a scintillation counter with a proportional chamber through a UV transparent window as proposed by Charpak, Policarpo and Sauli [28] (Fig. 18a). Good transfer efficiency of up to six photoelectrons per primary electron can be obtained by matching the scintillation spectrum of the *pure* noble gas used in the first chamber (e.g. krypton) with the photoionization cross-section of a complex molecule in the proportional chamber [e.g. triethylamine (TEA)] as shown in Fig. 18b.

4.2.2 Scintillation with electron multiplication. Although scintillation starts at a lower field than electron multiplication, it clearly does not stop at a high field. In fact Dolgoshein and co-workers [14] have observed a clear correlation between the amount of light produced and the electron multiplication (in the region of an amplification of 10). The light is

also mainly produced in the highest field region close to the sense wire, since it is partially shadowed by it.

Charpak and Sauli [29] have also shown that UV light is indeed produced in a parallel-plate multiplying structure. Filling both chambers of the system shown in Fig. 18a with argon (98%) and acetone (2%), they have observed signals in coincidence in both chambers (Fig. 19). They estimate that in a region of gain of 10^4 in their gas, the number of UV photons per ionizing collision is at least 10%.

4.2.3 Photon mediated multiplication. Such an effect clearly shows that photons can indeed take part in the avalanche. If an additive C of low enough ionization potential is included in low concentration in the gas, one can indeed observe the sequence

which can help in the multiplication process. Since ionization cross-sections are typically $5 \times 10^{-17} \text{ cm}^2$, the mean free path is

$$\frac{1}{\sigma N} = \frac{1}{5 \times 10^{-17} \times 2.69 \times 10^{19} \times 10^{-2}} \approx 0.07 \text{ cm} = 700 \text{ } \mu\text{m}$$

for 1% concentration of the additive and the avalanche size is increased.

However, a competitive effect very rapidly stops this phenomenon. As soon as the concentration of additive is large enough, so that the average time between the collision of the excited atom with the additive is small compared to the lifetime of the excited state, the Penning effect is dominant:

With an exchange cross-section of 10^{-15} cm^2 , there is an effective collision time of

$$\frac{1}{\sigma N v} = \frac{1}{10^{-15} \times 2.69 \times 10^{19} \times 10^{-1} \times \sqrt{2kT/m}} = 10^{-8} \text{ s} = 10 \text{ ns}$$

for $\sqrt{2kT/m} = 33000 \text{ cm/s}$ and a concentration of 10% at 1 atm. This is comparable to the lifetime of excited states, and the photon yield is sharply decreased and no longer participates in the avalanche.

However, photons again play a role in very large avalanches. In this case, the space charge of positive ions can decrease the electric field locally to such an extent that the electron multiplication cannot increase any more. At that time, photons emitted in the avalanche can escape and start a new avalanche a little further away from the wire or along the wire. This limited streamer or Geiger mode [30], depending on the direction in which photons propagate, is commonly observed at high gain with the usual mixtures (e.g. argon + isobutane). This mode gives rise to high pulses but also to large dead-times.

4.2.4 Multiplication at high pressure. As a final example of the analysis of basic phenomena at work, we will consider the problem of electron multiplication at high pressure. This can be stated as follows. The Townsend coefficient $\alpha(x)$ giving the rate of increase of the number of electrons

$$\alpha(x) = \frac{1}{n} \frac{dn}{dx}$$

is such that

$$\alpha/P = f(E/P) .$$

A typical behaviour of $f(E/P)$ is

$$f(E/P) = (E/P)^n \quad \text{with } n > 1 \text{ at low } \alpha.$$

In order to get a given α ,

$$E \sim P^{1-(1/n)}$$

Therefore E has to increase with the pressure, and it becomes increasingly difficult to reach high amplification.

Dodolkhov et al. [23] have noticed that by adding 0.5% Xe in argon at 100 atm the voltage of the operating point for a given amplification was decreased by as much as 30%. This can be explained by a Penning effect. Argon has, in addition to the family of excited states and metastable states at 11.5 eV, another family at 14.3 eV which is above the ionization threshold of Xe. We therefore have

as soon as the collision time with Xe is short in front of the excited state lifetime; that is, if the partial vapour of Xe is high enough.

At 100 atm an amplification of as much as 10^4 has been achieved.

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Figure captions

- Fig. 1 : Projection or imaging chamber.
- Fig. 2 : a) Feynman diagram for extraction of an electron.
b) Coherent scattering of the virtual photon.
c) Renormalization of the photon propagator through the index of the medium.
- Fig. 3 : a) Photoabsorption cross-section in argon.
b) Computed cross-section for extraction of electrons, showing the Rutherford (lowest) transverse photon and longitudinal photon resonance contributions (Ref. 9).
- Fig. 4 : a) Computed relativistic rise (full line) in the photoabsorption ionization model and experiment.
b, c) Landau fluctuation experimental histogram and theory (full line).
Dashed lines represent previous theoretical results.
- Fig. 5 : Loci of equal drift-time from the sense wires in JADE (Ref. 10).
- Fig. 6 : Preliminary results from M. Rijssenbeck with a pulsed X-ray system:
a) Computed spectrum.
b) Drift distance distribution without magnetic field.
c) Drift distance distribution with 7 kG magnetic field.
- Fig. 7 : a) Double-photon ionization process.
b) Double-step process.
(Ref. 18).

- Fig. 8 : a) Pulse observed with a UV beam parallel to the wire plane of an imaging chamber.
b) Pulse observed when the beam is perpendicular to the plane.
- Fig. 9 : Dependence of pulse height with laser intensity with 10^{-5} diethylaniline. Evidence for double-photon ionization.
- Fig. 10 : Dependence of pulse height with laser intensity without adding specifically any impurity in the gas:
a) From Hilke at 337 nm (Ref. 20).
b) From Bourotte and Sadoulet at 265 nm (Ref. 18).
- Fig. 11 : D_L and D_T for the JADE gas (Ref. 10).
- Fig. 12 : Computed energy distribution (a) and asymmetry (b) of electrons in argon for various electric fields (Ref. 1).
- Fig. 13 : Diffusion after 1 cm path of the electron swarm, σ_x , from the ϵ_k data for argon, CH_4 , C_2H_4 and C_3H_6 , and a theoretical estimate for an argon-isobutane (25%) mixture, for pure isobutane, for an argon-methane (10%) mixture (Ref. 1), and for argon-ethane (50%-50%) (Ref. 22).
- Fig. 14 : a) Drift velocity as a function of E/P in the JADE mixture (from Ref. 10).
b) Electron drift velocity as a function of the electric field at a pressure of 100 atm: 1) Ar + 0.5% Xe;
2) Ar + 0.5% Xe + 0.1% CH_4 ; 3) Ar + 0.5% Xe + 0.2% CH_4 ;
4) Ar + 0.5% Xe + 0.5% CH_4 ; 5) Ar + 0.5% Xe + 1.0% CH_4 (Ref. 23).
- Fig. 15 : a) Standard deviation on drift distances for various mixtures and pressures (J. Jaros, Mark II, private communication). Detection by electron multiplication.

- b) Standard deviation on drift distances in Xe at 20 atm
(Ref. 24). Detection by scintillation.

Fig. 16 : Noble gas scintillation mechanism.

Fig. 17 : a) Spectrum of emission of noble gases (Ref. 28).

b) Photoabsorption spectrum for C_2H_6 (Ref. 3).

Fig. 18 : a) Separation of gas volumes by a UV transparent window
(Ref. 28).

b) Photoionization cross-sections for various substances
(Ref. 28).

Fig. 19 : Pulses seen in coincidence across the UV transparent window
of Fig. 18a.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

a)

b)

Fig. 17

Fig. 18

Fig. 19