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INTRODUCTION

Inspired by embryonic ideas found in the early works of Charpak on Multiwire Proportional Chambers (MWPC)¹, and by the work of Allison², the Time Projection Chamber (TPC) concept was introduced by Nygren and collaborators in the years 1975-1976 for the needs of the PEP-4 detector³. The powerful imaging properties of the device and its particle identification capability has suggested the use of the TPC in many present and planned experimental setups, mainly around colliders where the nearly 4 π acceptance of the detector is best exploited. Copious experimental results obtained in operational devices begin to be available and generally agree with the expectations, with a few (but notable) exceptions, e.g. the so-called "hooks" or track distortions⁴ and the surprisingly strong dependence of the localization accuracy on the angle of tracks, the E x H effect⁵ (see also the other contributions to this workshop).

There is a general feeling that unpleasant surprises may still appear, and that some modifications of the original design (e.g. the choice of the wire and pad geometry and of the gas mixing) may result in improved performances. The purpose of these notes is, after a short discussion of some physical processes involved in the TPC-like detectors operation, to point out the areas where detailed information is still lacking and where problems have been found or may be expected. If possible, a solution or a line of research are offered to overcome the problems.

DRIFT AND DIFFUSION OF ELECTRONS IN GASES

Under the action of an electric field E, electrons produced in a gas at pressure P by an ionizing event drift towards the anode experiencing multiple collisions with the molecules and diffusing around the average trajectory (that follows the field lines). For an ideal "thermal" gas, where the average energy of the electrons is not increased by the field but remains $\epsilon=kT$, elementary considerations allow to deduce a linear increase of the drift velocity and an inverse decrease of the square of the diffusion width with E:

$$w = \frac{dx}{dt} = \frac{e}{m} \tau \frac{E}{P} \quad 1)$$

$$\sigma_x^2 = \frac{2kT}{e} \frac{x}{E} \quad 2)$$

where τ is the mean electron-molecule collision time and x the drift distance along the field. In some gases the average (or characteristic) energy ϵ remains thermal up to rather high values of field, as in CO_2 (said to be a "cool" gas); in Argon, on the other hand, even small values of E increase considerably the electron energy. Figs 1 and 2 show the experimental values for w and ϵ in CO_2 and Argon respectively ^{6,7}. In both gases, the drift velocity is a linear function of E until electrons are "heated up" by the field, above $\sim 2 \text{ kV/cm.Atm}$ in CO_2 and $\sim 1 \text{ V/cm.Atm}$ in Argon. The diffusion law can be generalized simply introducing the characteristic energy in expr. 2):

$$\sigma_x^2 = \frac{2\epsilon}{e} \frac{x}{E} = \frac{2\epsilon}{e} \frac{P}{E} \frac{x}{P} \quad (3)$$

(the second formulation shows the inverse dependence on the gas pressure, at a given value of E/P).

Fig. 1 Characteristic energy, drift velocity and diffusion (for one cm of drift at atmospheric pressure) in CO_2 , as a function of the electric field.

Fig. 2 Characteristic energy, drift velocity and diffusion in Argon.

In Figs 1 and 2 the standard deviation of the diffusion is represented for one cm of drift, and compared with the thermal limit given by 2).

The different behaviour of various gases is explained by the dependence of the total molecular cross section from the electron energy, as shown in Fig. 3 for A and CO_2 ^{6,7}. When increasing the field, electrons in Argon are accelerated and find a very quickly decreasing cross section, the so-called Ramsauer dip: the gas becomes "transparent" and electrons acquire easily high energies. In CO_2 , on the other hand, the cross sections are higher and the decrease much less pronounced; most molecular gases have a similar behaviour. It is then clear what happens when adding even small quantities of CO_2 to Argon: the CO_2 cross section will dominate, "filling" the Ramsauer dip, and thermalizing or "cooling" the electrons. The same effect, to various extent, is obtained adding other molecular gases as the hydrocarbons.

The large range of values and behaviour of the molecular cross sections results in drift velocities having various shapes and spanning more than an order of magnitude in values at a given field. Fig. 4, a compilation from ref. 8, shows the drift velocity in various pure gases and Fig. 5 experimental values for A.CH_4 mixtures ⁹.

Fig. 3 Total cross sections as a function of electron energy in A and CO₂.

Fig. 4 Drift velocities for electrons in various gases, as a function of electric field.

Fig. 5 Drift velocity as a electrons in various gases as a function of field (at one Atm) for A.CH₄ mixtures.

Detailed theories have been developed to describe the electron drift and diffusion in gases; they are reviewed by Palladino and Sadoulet ⁸, Schultz and Gresser ¹⁰, Matheson and El Hakeen ¹¹. If the respective total and elastic cross sections are known, the energy distribution, drift velocity and diffusion properties can be computed for pure gases and their mixtures. As an example, Fig. 6 shows the experimental and computed dependence of w on E for A-C₂H₆ mixtures ¹².

Fig. 6 Computed and experimental values of drift velocity in various A.C₂H₆ mixtures.

Fig. 7 shows the computed dependence of the diffusion standard deviation, σ_x , for one cm of drift at atmospheric pressure; it has been computed through expr. 3 from the value of ϵ (the value of σ_x for different drift lengths and pressures can be deduced through expr. 3). Inconsistencies appeared very soon however between these classical values and experimental results obtained in drift chambers. The point is that the classical theory considers the diffusion process to be symmetric; there is evidence that, at least in some gases and at high values of the field, the longitudinal and transverse diffusion can be rather different ¹³. Fig. 8 shows for example the ratio D/μ , diffusion coefficient over mobility (equal to the characteristic energy ϵ) for a gas mixture used in the Jade detector ¹⁴, both for transverse and longitudinal diffusion. Around 1 kV/cm.Atm, D_L is about four times smaller than D_T and the space diffusion therefore twice smaller. Notice that all results of the classical theory were at the origin provided by a measurement of transverse diffusion, and therefore they only can reproduce this value. Only modern techniques, using drift chambers and pulsed ionization sources, allow to measure the longitudinal diffusion.

Fig. 7 Space diffusion for one cm of drift at atmospheric pressure, computed for various gases.

Fig. 8 Longitudinal and transverse diffusion coefficients measured as a function of electric field.

Fig. 9 shows a comparison of experimental data for the longitudinal diffusion measured in various gas mixtures with the previous calculations (A-CH₄, A-CO₂ from Piuz ¹⁵; A-C₄H₁₀-Methylal, in the proportions 67.2, 30.3, 2.5 from Breskin, Charpak and Sauli ¹⁶; C₂H₄-Methylal from Walenta ¹⁷).

Fig. 9 Computed values of the space diffusion (as in Fig. 7) compared with some recent experimental values of longitudinal diffusion.

From this very wide range of possible drift velocities and diffusion properties the experimenter can choose the mixture that best suites his experimental needs, e.g. a fast gas at low fields for long drift chambers (the standard TPC choice), a gas with saturated velocity for good accuracy drift chambers ¹⁸ or with small velocity and small diffusion in the time expansion chamber ¹⁷. As we will see later, other requirements may restrict the choice (e.g. energy resolution, Lorentz angle in crossed magnetic and electric fields). Needless to say, for TPC detectors the gas should have a negligible electron attachment.

One peculiarity has been often neglected, the dependence of drift velocity on temperature. While for a thermal gas this is simply given the density variation, or by $\Delta T/T$, (see expr. 1),

for "hot" gases the effect can be estimated from the E/P dependence of the drift velocity; it may be very small or even negative. Fig. 10a shows computed values of the relative variation $\Delta w/w$ (in parts per thousand per °C) as a function of E in various gases ¹⁰; the cross is an experimental point in A.C₄H₁₀.Methylal ¹⁶. Fig. 10b shows the same dependence measured in a typical TPC gas, A.CH₄ in the ratio 80-20 ¹⁹. Obviously, the choice of a "cold" gas in view of reducing diffusion, or of low electric field values may result in a large temperature variation of the drift velocity; notice that $\Delta w/w$ of 10^{-3} implies a shift in the recorded vertical coordinate (measured through the drift time) of 1 mm per °C of temperature variation.

Fig. 10 a) Field dependence of the relative temperature variation of drift velocity, computed for various gases.

EFFECT OF MAGNETIC FIELDS

When an external magnetic field is applied to the drifting electrons, their energy repartition is modified and both drift velocity and diffusion properties are different. If the electric and magnetic fields are strictly parallel, the drift trajectories are left unchanged, which is the case in the TPC drift volume (at least, in absence of local field distortions). When approaching

the cathode grid or grids (e.g. if gating is implemented) and then the anode wire mesh, electrons follow curved paths and experience therefore strong $E \times H$ forces with consequent track distortion and loss of localization accuracy 4,5. It is appropriate to recall here some elementary theory and measurements of drift velocity and angles in crossed E and H fields.

For the particular case of perpendicular fields (the general case can be treated by vectorial composition), again using elementary kinetic gas theory one obtains the following expressions for the magnetic drift velocity ω_H and the drift angle θ_H :

$$w_H = \frac{w}{\sqrt{1+\omega^2\tau^2}} \quad \omega = \frac{eH}{m}; \tan \theta_H = \omega\tau \quad 4)$$

where, in crude approximation, the average collision time τ can be approximated by its $H = 0$ value. Taking expr. 1) at face value, i.e. including in a phenomenological field-dependent $\tau = \tau(E)$ the deviations from linearity observed for w , one can rather well match the experimental values of drift velocity and angle, at least for low values of electric field; an example is shown in Fig. 11 and Fig. 12 18. Experimental values of θ_H for some gas mixtures are given in Fig. 13 18; similar measurements have been made in $A-C_2H_6$ and $Xe - C_2H_6$ 20. Fig. 14 shows the drift angle as a function of fields computed for $Ar CH_4$ and $Ar C_2H_6$ mixture, using a similar simple model 21. The general tendency is as follows: for a given value of H , the drift angle is large at low fields for the gases in which the drift velocity increases rapidly with E (large τ) and is therefore larger for faster gases as in $A CH_4$; when the velocity levels off (decreasing τ) the angle decreases. One expects therefore large $E \times H$ effects in $A CH_4$ mixtures operated at moderate fields. Notice that the deflection should be particularly small in slow gases, an effect described by Beker et al 22. In fig. 15 we have plotted the values of θ_H measured, at 5 kG, as a function of E for the $A.C_4H_{10}$.Methylal mixture (see Fig. 13) and for the slow $CO_2.C_4H_{10}$

Fig. 10 b) Experimental measurement of the dependence for $A.CH_4$ (80-20).

Fig. 11 Average electron collision time for an A.C₄H₁₀ Methylal mixture, deduced from expr. 1.

Fig. 12 Magnetic field dependence of drift velocity and angle, computed with expr. 4 using the values of τ from Fig. 11, compared with experimental data.

Fig. 13 Experimental values of drift angle as a function of magnetic field.

Fig. 14 Computed dependence of the drift angle at 13 kGauss from electric field, in A. CH_4 and A. C_2H_6 .

mixture 22; so small drift angles were really unexpected before this measurement. The same authors have measured drift angles at extreme values of magnetic fields 23.

The effect of magnetic fields on the drifting electrons can be easily included in the rigorous theory, as discussed for example by Palladino and Sadoulet 8 and by Ramanantsozohena 12. Fig. 16 shows for example a comparison between the experimental measurements of Daum et al. 20 in A. C_2H_6 and the results of the transport theory 12.

Fig. 15 Experimental values of drift angle for a conventional MWPC gas, as given by Fig. 14, and for a slow $CO_2C_4H_{10}$ mixture.

Fig. 16 Experimental values of drift angle in magnetic field compared with the transport theory calculation, in $A.C_2H_6$.

The transverse diffusion of drifting electrons is considerably decreased at high values of the magnetic field in some gases, and in A.CH₄ in particular, an observation that indeed suggested the choice of this mixture in the TPC³ while it remains almost constant in A.CO₂ mixtures (see Figs 17). Notice however that the longitudinal diffusion is not modified by the presence of a magnetic field.

As one can see, also the magnetic properties of drifting electrons very considerably from one gas to another. Again, the experimenter has to tailor the mixture to its needs, a choice that is often difficult to make because of the fragmentary and scattered experimental results.

Fig. 17 Reduction of transverse diffusion in strong magnetic fields for A.CH₄ mixtures.

UNDERSTANDING ENERGY RESOLUTION: THE PROPORTIONAL AMPLIFICATION

The TPC design adds to the powerful tracking properties a limited particle identification capability, obtained through multiple sampling of the differential energy loss. The resolution power is largely dominated by the statistical fluctuations in energy loss of fast particles in thin samples of gas, and by the limited extent of the relativistic rise; however one should not forget that the process of charge multiplication in the detector may partly spoil the expected resolution or introduce systematic shifts (e.g. through angular effects).

Let us consider a simplified picture of the avalanche process around a thin wire started by a single electron (Fig. 18²⁴). In the fast increasing field, an

Fig. 18 Simplified representation of the avalanche process around thin wires.

electron approaching the wire experiences inelastic ionizing collisions producing electron-ion pairs; being several thousand times faster, the electrons move in the front of the avalanche and are collected by the wire within a fraction of a nsec. Ions left behind recede with decreasing speed, inducing the detected signal. Both direct and photon-propagated diffusion help spreading the avalanche around the wire, the more the higher the gain ^{25,26}. The statistical fluctuations in the size of the avalanche produced by a single electron contribute to the energy resolution that can be achieved with a proportional counter; one can write indeed, in a simplified formulation and disregarding external noise sources:

$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{\sigma_N}{N}\right)^2 + \frac{1}{N} \left(\frac{\sigma_A}{A}\right)^2 \quad 5)$$

where σ_N/N is the relative dispersion of the charge deposited in the gas, and σ_A/A the variance of the avalanche produced by one electron. Mainly for the needs of soft X-rays spectroscopy, a considerable effort has been put into the understanding of the second term in expr. 5 and in finding suitable wire geometries and gas mixtures to minimize its contribution. As an example Fig. 19 shows the computed variance $f = (\sigma_A/A)^2$ as function of the average gas gain and wire diameter, for Argon ²⁷. Notice that at moderate

Fig. 19 Computed dependence of the avalanche fluctuation from the average gain and the product P.r, pressure times wire diameter at fixed gain, in Argon.

gains, 10^2 or so, the variance is already close to its maximum value and there is not much difference with the resolution obtained at higher gains (space charge effects change this picture, see later). A good account of the efforts to improve energy resolution in proportional counters, e.g. by using Penning gas mixtures, is given by Sipilä ²⁸. Fig. 20 shows some results obtained in detecting 5.9 keV X-rays in various gases, at increasing gains ²⁹; the decrease of resolution at low gains is due to electronics noise. While the best results in absolute sense are

obtained using the Ne-Ar Penning mixture, the fluctuation is in this gas increasing at a faster rate than in the other mixtures. Another example of gain-dependent resolution for various gases is given in Fig. 21 30, for A-C₂H₆ mixtures; notice the very different behaviour towards high gains. A natural question then arises: is the original TPC design decision to operate at gains around 10^3 for best energy resolution justified or can one find conditions where the gain can be increased without much loss (with obvious advantages from the electronics point of view)? Fig. 21 shows that, at least in an Argon-Ethane mixture (15-85, which may not be practical for other reasons) the resolution can be as good at gain of 10^5 than it is at 10^3 .

Unfortunately this is not all the story: it appears indeed that for charged particles (all previous measurements were made using soft X-rays) the behaviour can be different. Fig. 22 shows a measurement realized using a spherical proportional counter 31 on fast protons and hard X-rays (producing a photoelectron with considerable range in the gas). There is obviously a critical value for the total detected charge, about 10^6 electrons, above which resolution quickly degrades.

A classical explanation for the effect is that the presence of high ion densities in the avalanche produces a space charge gain reduction; this is indeed experimentally observed (see for example Walenta 32). It is not obvious however why a gain reduction should result in an increased dispersion. Only in the recent years, and with the help of the tracking capabilities of gas detectors developed for high energy physics, the reason has been found to lay probably in the slight dependence of the gain on the detailed time structure of the detected charge (i.e. on the tracks' angle) even at small gains. Positive ions produced in the early avalanches modify locally the electric field and therefore reduce the gain; the integral effect depends of course on the geometry (if the track is detected on a long section of a wire the effect will be smaller). The effect has been studied for example by Frehse et al 33; some of their results are shown in Fig. 23. In the figure, the ordinate is the normalized detected pulse height

Fig. 20 Experimental values of energy resolution as a function of proportional gain in various gases (on 5.9 keV X-rays)

Fig. 21 Energy resolution for 5.9 keV X-rays in various A.C H mixtures, as a function of proportional gain.

Fig. 22 Proportional counter resolution vs. gain, measured for two sources of extended ionization, 585 keV protons and 60 keV γ rays.

(amplitude divided by track length) for various angles of incidence to the anode wire in a MWPC (0° meaning a track perpendicular to the wire plane). Even at gains of 10^4 , there is a 30% difference in the apparent gain, certainly a major effect.

Fig. 23 Angular dependence of normalized pulse height vs. gain, measured for minimum ionizing particles in a MWPC.

Similar measurements have been published recently, obtained at much lower gains in the detection of α particles ³⁴. Notice that in TPC-like detectors the angle of the track in respect to the wire is accurately known, and the gain angular dependence can in principle be corrected for. Can this be used to obtain good resolution at high gains, where the effect is larger? And is there any gas mixture and wire geometry where the gain variations are smaller? These questions have not received so far a satisfactory answer and the field is open for research.

FLUCTUATIONS IN IONIZATION LOSSES AND THEIR CONSEQUENCES

We have dealt in the previous section with the second term in expr. 5 providing the energy resolution. Let me now consider the first term, i.e. the fluctuation in the number of charges produced in the gas by ionization. For fast charged particles, the process of ionization consists in a small number of primary interactions (20 ± 30 per cm at atmospheric pressure) each with a given energy transfer: small transfers, resulting in the creation of a single electron-ion pair are the most probable, but larger transfers, where the electron has enough energy to further ionize, may occur. The energy distribution of ejected electrons (often referred to as δ -electrons) is in first approximation inversely proportional to its energy square, and the probability of getting a δ -electron in a given segment of track with energy equal or greater than E_0 is proportional to $1/E_0$. For example, in one cm of Argon at STP one track out of ten contains a 1 keV electron ³⁵ (the average energy loss being 2.5 keV/cm).

A modern version of the theory describing the energy loss processes in thin samples has been written by Allison and Cobb ³⁶; a detailed phenomenological calculation of δ -electrons distribution is given in a paper by Lapique and Piuz ³⁷. The peculiar statistics that results has two consequences: on one hand, the energy loss distribution in thin layers of gas is very wide, with a FWHM almost equal to its average (Fig. 24). Multiple sampling over several hundred independent segments and high pressure operation is necessary to determine the averages with sufficient accuracy to attempt particle identification. Moreover, even within a given segment of track, the energy loss distribution can be very asymmetric with most of the charge concentrated in a single cluster; this has serious consequences on the localization properties of the detector.

Fig. 24 Experimental and computed energy loss distribution of fast charged particles.

It has been realized by several authors that in some gases, CO_2 and the hydrocarbons, the single layer energy resolution is

better for a given thickness than for mixtures containing mainly a noble gas 38,39. Fig. 25 shows the relative variance of the ionization losses as a function of gas thickness, in various gases 39; for example, in a 4 cm thick sample at 1 atmosphere the relative resolution in hydrocarbons is almost twice better than for an A-CH₄ mixture. In Fig. 26, from the same source, the difference is even more obvious. Does this imply that one should try to replace noble gas fillings with hydrocarbons in all TPC's? This is not so far two reasons. The first is purely technical: the operational voltage for the end-cap MWPC would have to be almost doubled using a gas very rich in hydrocarbons, and the drift velocity and properties in the new gas would probably not satisfy the experimental requirements. The second reason is however more fundamental: what happens to the relativistic rise (the difference in ionization density that allows particle identification at high momenta) in hydrocarbons? The answer is that the rise is smaller and that saturation is reached sooner, see Fig. 27 40. There seem to be a simple dependence of the amount of relativistic rise from the molecular properties of the medium, which does not leave much space for "new" better gases, as shown also by Walenta 41. Nevertheless, in some restricted momentum regions, the particle separation can indeed be improved 39 and this certainly applies to the region of velocity before the minimum of ionization. It is conceivable for example that a TPC designed to identify slow heavy ions can profit from the improved energy resolution in individual samples.

Fig. 25 Relative energy loss resolution for various gases, as a function of the layer thickness and pressure, for minimum ionizing particles.

Fig. 26 Relative energy resolution for fast particles in a 4 cm thick layer of various gases, as a function of molecular weight.

Fig. 27 Relativistic rise in the energy loss of fast particles, for some gases at atmospheric pressure.

The second consequence of the wide energy loss distribution concerns the localization accuracy. Both the drift time and the centre of gravity measurements are affected, the second one being particularly sensitive to charge asymmetries. The error in the vertical coordinate, obtained from a drift time measurement, is not restricted to the simple increase in track size due to long-range δ -electrons (although this is not a negligible factor ⁴²).

There is indeed a larger effect due to the focussing properties of the cathode mesh, as discussed for example by Va'vra ⁴³. When approaching the anode plane electrons reach the anode at different times, even for a track parallel to the wire plane, because of the slope of the field lines around the cathode and at the anode; a large cluster at a given position will tend to offset the timing information, obtained generally with a simple threshold discriminator. For inclined tracks and in presence of $E \times H$ effects, the timing errors are obviously much larger.

Fig. 28, the result of an accurate computer simulation developed by Va'vra, shows the overlap of several pulses detected in a drift chamber under the conditions described in the drawing. Various methods of improving the drift time measurement are discussed by the same author; the best would be, of course, to record the full shape of the detected pulses for further detailed analysis, a possibility that may be not so remote with the quick advances in microelectronics.

The effect of charge asymmetry on positioning accuracy when using the centre of gravity localization method has been measured accurately by Charpak et al ⁴⁴ in a bi-dimensional proportional chamber with cathode strips readout. Fig. 29 shows one of their results: the space accuracy obtained for minimum ionizing particles is given for various angles of incidence (0° being a track perpendicular to the wire plane) and as a function of the energy loss. Not only is the accuracy for inclined tracks much worse than for the perpendicular ones, but also there is a clear correlation

Fig. 28 Computer simulation of charge signals detected in a drift chamber.

Fig. 29 Angular dependence of localization accuracy measured in a cathode readout MWPC, as a function of energy loss O .

between accuracy and energy loss. All these effects are emphasized by the presence of a magnetic field with its resulting $E \times B$ distortions near to the anode wires; they are extensively discussed by the authors of ref. 5, by Amendolia et al 45 and in other contributions to this workshop.

In order to reduce the effect, various authors have analyzed alternative cathode geometries that may be implemented to reduce the field line distortions. A completely new approach, using as end cap detector a Parallel Plate Chamber, has also been proposed 46,47. I will here only recall one consequence of the previous considerations on the relative width of the energy loss in various gases (Figs 25 and 26): it seems obvious that in a gas with less energy loss fluctuation the distortion effects that are caused by asymmetries in energy deposit should be smaller. This certainly seems worth an experimental verification, or a detailed calculation using one of the many simulation programs developed in most groups operating or intending to use a Time Projection Chamber 43,48,49.

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