MEASUREMENT OF THE LONGITUDINAL DIFFUSION OF A SINGLE ELECTRON IN GAS MIXTURES USED IN PROPORTIONAL COUNTERS

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Drift velocities and coefficient of longitudinal diffusion are measured for a single electron by a time-of-flight technique. The gas mixtures which were investigated are argon (or neon) with ethane, carbon dioxide, and methane with or without methylal admixture. The limits of accuracy of this method are discussed.

1. Introduction

We describe in this paper the measurements of some transport parameters of a single electron in different gas mixtures commonly used in charged particle detectors. The experimental technique in use was a time-of-flight (TOF) measurement. Applied to a single electron, this is the most direct method to study specifically the longitudinal diffusion in comparison to other approaches involving photon sources or pencil beams of charged particles [1,2], which generate clusters of electrons. However, what will be the ultimate limitation of the measurement accuracy are the fluctuations expressed in time unit on the start and stop signals compared to the diffusion size to be measured. The estimate of this limitation has been investigated by a proper choice of the gas mixtures under study.

On one side, we looked at mixtures having a slow drift velocity (few mm/ μ s) and a characteristic electron energy ϵ_k close to its thermal value, kT . Such are mixtures comprising carbon dioxide or methylal. These features are in fact suitable to the determination of the energy loss of ionizing particles by means of "longitudinal drift" technique such as small sample pulse heights or digital cluster counting analysis [3,4]. Slow drift velocity is desirable as it allows a good time separation between clusters. However, the knowledge of the coefficient of longitudinal diffusion is of prime importance as this effect is responsible for the blowing-up of the primary clusters when they move towards a detection wire, destroying then the energy loss pattern, associated to the initial cluster size [5,6]. Now, on the side of higher drift velocities (50–100 mm/ μ s) and $\epsilon_k > kT$, binary mixtures such as Ar/CH₄ or Ar/C₂H₄ (ethane) will allow us to estimate the ultimate capability of the TOF method. At this velocity range, the coefficient of longitudinal diffusion is again of interest. A well known

example relates to the track localization in detectors where the secondary electrons drift over very large distances (20–100 cm) and their detection, made at the same wire in two orthogonal directions, can be greatly affected by diffusion effects possibly anisotropic. See for example all the development work about the time projection chamber (TPC) [7] and the ISIS projects [8] where the determination of electronic transport parameters has been carried on by various methods (simple electron sources).

2. Experimental set-up

2.1. Method

By means of a flash of UV light, photoelectrons are extracted from the outer electrode of a parallel plane gap, where a dc field E has been established (fig. 1). A signal, provided at each light pulse starts a time-to-amplitude converter (TAC). Electrons after having travelled through the gap over a distance L traverse a transparent mesh electrode, to be multiplied at a wire belonging to a thin MWPC constituted by this mesh and a third electrode kept at the same potential. The signal, developed at the wire gives the stop signal to the TAC. Let us call t the drift time associated to L : a distribution of t (time distribution) can be recorded, with a mean and standard deviation t_m and σ_t .

According to the solution of a one dimension transport equation, this distribution is found to be Gaussian [9]

$$\Delta N/\Delta t \propto (4\pi Dt)^{-1/2} \exp\left[-(L - v_D t)^2/4Dt\right], \quad (1)$$

where v_D is the drift velocity and D the diffusion coefficient. The longitudinal dispersion σ_L is related to D by $\sigma_L = \sqrt{2Dt}$ or

$$\sigma_L = \sigma_{0L}\sqrt{L}, \quad (2)$$

Fig. 1. Experimental set-up and electronic block diagram. A, B: drift gap and detection chamber; L, RC: flash lamp and circuit; L_1 , L_2 , FI: lenses and fibers; D: discriminator; DEL: delay; F: linear fanout; G: generator of delayed gates for ADCs. Output 1: time distribution; 2: event trigger; 3: pulse height sampling.

where the dispersion σ_{0L} is defined for 1 cm of drift length. Assuming $L \gg \sigma_L$, one has $v_D = L/t_m$ and

$$\sigma_{0L} = \sigma_L v_D / \sqrt{L}, \quad (3)$$

which are the quantities that will be looked for in the following.

2.2. Chamber and light source

The drift volume is of dimensions $12 \times 12 \times 3 \text{ cm}^3$, surrounded by guard planes spaced by 5 mm and raised at convenient graded potentials in order to ensure a good field homogeneity (fig. 1). The MWPC has the following parameters: 3 mm gap, 2 mm wire spacing, $15 \mu\text{m}$ wire diameter. The separation electrode is made of a mesh of $500 \mu\text{m}$ square, $50 \mu\text{m}$ wire $\varnothing$. The chamber array is enclosed into a metallic vessel which can be pumped down to few 10^{-2} Torr. The purity of the different gases used was always better than 99.9%.

The UV light source is a hydrogen filled lamp* operating as a spark gap overvolted by a simple RC circuit (fig. 1). The light flash has a duration of $\sim 7 \text{ ns}$ fwhm and a continuous emission spectrum peaked around $2700 \text{ \AA}$. The start signal can be derived either

from the circuit supplying the lamp (discharge current) or from a photomultiplier illuminated by an independent quartz fiber. These two pulses are shown in fig. 2. By means of lenses and quartz fiber, the light is focused at a spot of few mm^2 on the outer drift electrode where a thin zinc sheet has been fixed. Such an array was capable to produce $\sim 1\text{--}3$ photoelectrons/s when the lamp was operated at $\sim 1 \text{ kHz}$ repetition rate.

Fig. 2. Start signal (a) from the photomultiplier (DUVP 56) 5 ns/div; (b) from the RC circuit (coaxial shunt) 5 ns/div.

* Product of Racah Institute of Physics, Dr. I.B. Berlman, Jerusalem.

Fig. 3. Stop signal from the MPWC (a), ^{55}Fe source; (b) single electron 10 ns/div.

2.3. Electronics

The preamplifier attached to the detection wire is a fast voltage amplifier ($R_{\text{input}} = 400 \Omega$) followed by a zero pole cancellation filter. Its response to a Fe^{55} source and a single electron, is seen in fig. 3 and shows an occupation time of 30 ns at the base line and a 2 ns rise time. This signal, after further amplification, triggers a discriminator (LRS 821 CS).

3. Measurements

3.1. Single electron identification

Fig. 1 shows the block diagram of the electronics used to record the time distribution. The measurement of the drift time is shared in two parts: the start signal is delayed by a fixed quantity (first part, DEL1), chosen in a way that the span of fluctuations of t is covered with the best time resolution of the TAC (second part).

An event trigger is obtained by a coincidence between the wire signal and the delayed start signal, previously adjusted around the stop value, and wide enough to prevent any truncation of the distribution. Although the procedure selects those events having pulse heights above an amplitude threshold, it allows a necessary reduction of the trigger rate of the lamp alone as the photo-electron yield is of low efficiency. However, spurious cosmic ray events may be recorded when they occur in time with the start window. As shown in fig. 4, they will appear as a train of separated pulses or a pulse wider than 30 ns, depending on the orientation of the track into the chamber. Parasitic triggers (noise) may also be recorded as a train of pulses.

We shall take as a criterion of a “photoelectron”

event, the identification of a single narrow pulse (~ 30 ns) into a time window comparatively much wider. This was achieved by means of a pulse height sampling of the wire signal done in the following way. The wire pulse is delayed (DEL2 = 100 ns in fig. 1) with respect to the event trigger and fanned out into the inputs of two analog to digital converters with separated gates*: 24 gate signals of 20 ns width are generated from the same source, delayed with respect to the other in a way that the falling edge (~ 1 ns) of the i th gate overlaps the rising edge of the $(i + 1)$ th one. The sample window was then of 480 ns width. In this way, a single pulse associated to a trigger, will always be sampled into the same gates – in our case, that was the 4th and the 5th – while it is possible to determine whether the trigger was preceded and followed by other pulses as typically observed with ionizing tracks (fig. 4). In addition, when a slow drift velocity was used ($2\text{--}3 \text{ mm}/\mu\text{s}$), the occurrence of more than one photoelectron into the sampling time was not observed. A selection of “photoelectron events” is thereby easily made at the software level as demonstrated below.

3.2. Pulse height measurements

We take as an example of single electron selection a measurement made in an argon- CO_2 20% mixture where the drift velocity and the longitudinal diffusion were respectively $8 \text{ mm}/\mu\text{s}$ and $190 \mu\text{m}/\sqrt{\text{cm}}$. A typical behaviour is shown in fig. 5. The pulse height (PH) spectra are numerated accordingly to their gate time sequence. The non shadowed distributions, seen in the PH histograms 1 to 6, are obtained with the two software requirements that (a) their events belong to the time distribution and (b) all events having in spectrum 1 a PH greater than the ADC channel 60 are rejected. The three first histograms show then only pedestal noise distributions, while the next two are PH of signals, the largest amplitudes giving some contribution not beyond histogram 6. The following distributions (18) are not shown here as they are again pedestals. When the (b) selection requirement is removed, the contribution of spurious extra pulses is represented in spectra 1–3 in a shadowed area. For simplicity, we did not draw in this case, the corresponding pedestal peaks into 1, 2, 3 and PH distributions in 4, 5, 6 as they are slightly modified with respect to the preceding spectra. It is therefore apparent how this procedure is able to select single narrow pulses characterizing photo-electrons.

It is known [10] that the pulse height, a , induced by the avalanche issued from a single electron should have, in the first approximation of a proportional amplification, an exponential distribution, that is

$$dN/da \propto \exp[-a/\bar{a}_0]. \quad (4)$$

* Le Croy 2249 SG – charge sensing, 10 bits.

Fig. 4. MWPC signal of a minimum ionizing track about perpendicular to the chamber, 100 ns/div. $E = 100$ V/cm, argon-methane-methylal.

Fig. 6. Pulse height spectrum of a single electron in argon- CO_2 20%.

Fig. 5. Pulse height spectra corresponding to the 6 first ADC gates (20 ns width) demonstrating the “single electron” selection (sect. 3.2).

Fig. 7. Mean pulse height of single electron spectra vs discrimination threshold.

The spectra of figs. 5 and 6 are cut on their left side by the application of the discriminator threshold level, say A . Let us call $\bar{a}$ the mean of such a truncated distribution. There is a simple way to estimate $\bar{a}_0$, the mean pulse height in absence of threshold. From eq. (4), one can derive

$$\bar{a} = \bar{a}_0 + A.$$

Taking several measurements at different thresholds, such a linear behaviour is observed, as shown in fig. 7, which, by extrapolation allows to determine $\bar{a}_0$. This value, $\bar{a}_0 = 44$, is found to be in good agreement with the one obtained directly from the slope of the curve in fig. 6, that is $\bar{a}_0 = 46$.

Finally, $\bar{a}_0$ has been compared to the mean pulse height obtained in the same conditions – high voltage, PH analysis – from a ^{55}Fe source, after convenient electronic amplification adjustment. The 5.9 keV photons are then converted into the detection MWPC by cancelling the drift field into the 30 mm gap. A ratio of 210 ± 10 is found between the two values, which is fairly compatible with the expected number of electrons created by such photons in argon, that is 220.

Under the assumption of relation (4), the plot in fig. 5 allows an estimate of the one electron detection efficiency: the expected total number of events, N_0 , can be known by extrapolating the exponential line to $a = 0$. The efficiency will be $\epsilon = N/N_0$ where N is the actual number of events recorded into the spectrum. A value of ϵ of ~ 70 – 80% is typically found which might be a lower limit: it is known [11] in fact that, at the low amplitude region of the PH spectrum the exponential shape assumed here should be replaced by a peak shaped distribution such as $(a/a_0)\theta \exp[-(1+\theta)a/a_0]$ (Polya distribution with $\theta < 1$) which will then reduce N_0 .

Fig. 8. Stop time distributions, measurements and Gaussian fits (725 Torr). (a) A-CO₂ 20%, $E = 800$ V/cm, $v_D = 41.5$ mm/ μ s; (b) A-CO₂ 20%, $E = 70$ V/cm, $v_D = 2.72$ mm/ μ s; (c) A-CH₄ 20%, $E = 105$ V/cm, $v_D = 53.1$ mm/ μ s; (d) A-CH₄ 20%, $E = 800$ V/cm, $v_D = 44.2$ mm/ μ s.

3.3. Time distribution measurements

These quantities were measured in several gas mixtures such as argon-CO₂ 20%, argon-methane and methylal classified as “slow” in comparison to binary hydrocarbonated mixtures argon-methane, argon-ethane. Neon mixtures and pure methane were also investigated.

The drift distance of 30 mm and the gaseous amplification were kept identical for the different mixtures, which leads to an operating voltage of the MWPC of 2000–2200 V.

We show in fig. 8 various time distributions obtained at different field strengths in argon-CO₂ and argon-methane; the event selection has been done as described in sect. 3.2. Depending on the field strength, the different TAC sensitivities used were 360, 144, 57.5 ADC channels corresponding to 100 ns. The mean drift time is obtained by summing the contribution of the average of the time distribution and the fixed delay including the transit time through the electronics. The gaussian fit which provides the standard deviation σ_t of these distributions is drawn in fig. 8. We remark that the spectra were always found perfectly symmetric in case of “slow” mixtures as illustrated in figs. 8a, b, c; this is not the case in argon-methane and argon-ethane at field strength larger than 300–400 V/cm as seen in fig. 8d. The origin of this skewness will be discussed in the following section.

4. Source and evaluation of errors

We shall first list the different sources of errors present in our TOF method and discuss afterwards their influence on v_D and σ_{0L} .

(a) If a negligible time lag is assumed between the action of the UV light at the surface and the extraction of a photo-electron [12], the pulse shape of the light signal can be taken as the time distribution of the start signal. Assuming it has a Gaussian shape, the start error is equal to its standard deviation, σ_{start} . The fwhm of the light pulse is estimated from fig. 2 to ~ 7 ns, then $\sigma_{\text{start}} \approx 3$ ns. However, the very low efficiency of the photo-electron yield ($\sim 10^{-3}$) may suggest that their emission occurs near the maximum intensity of the light, which could reduce this estimation.

(b) The fixed delay DEL1, the transit time of the signal through the electronics elements, TAC included, can be measured with an external pulse generator within an $\pm 1\%$ accuracy. The effect of the threshold of the wire discriminator has been found of negligible influence ($\sim$ ns).

(c) The shortest path of the photoelectron through the gap follows a line perpendicular to the electrodes and passing by the detection wire. An increase in drift

length may occur from a transverse displacement of the starting and arriving positions of the electron with respect to the intersections of this line with the electrodes. This may be due to the extension of the light spot and the cumulative action of the lateral diffusion along the drift length. Assuming such an offset to be 1.5 mm only at the outer electrode, this would lengthen the drift path to the wire (no offset) by $37 \mu\text{m}$ (1.2‰).

(d) On the other hand, a slight reduction of the effective drift length can be associated with the fact that the high field of the MWPC (~ 4 kV/cm) extends its influence through the mesh electrode into the low field drift gap. At a drift field of 400 V/cm, this enhancement should be sensible in a layer estimated at $200 \mu\text{m}$, reducing the drift length by less than a 1%.

(e) Finally, one has to subtract from the drift time the collection time of the electron into the MWPC. Referring to fig. 9a, this quantity varies with the position x at which the electron traverses the mesh electrode. Let us call l the length of a field line followed into the MWPC by an electron from a point $P(x, l_0)$ at the cathode to the wire surface. We plotted in fig. 9b the ratio l/l_0 in our experimental conditions using the equation of a field line [13]

$$\tanh \pi y/s = \text{tg } \alpha \cdot \text{tg } \pi x/s, \quad (5)$$

and

$$dl^2 = dx^2 + dy^2.$$

The knowledge of the drift velocity at the field value $*$ into the MWPC allows to derive the collection time. An accurate measurement of l was out done in our experiment but we estimated the fluctuations of the collection time as follows. By means of a Monte Carlo simulation, we generate a distribution of stop times which are calculated as the sum of two terms. The first one, expressed in time units, corresponds to the longitudinal diffusion after the drift distance L and is drawn from a Gaussian distribution of rms $\sigma_D = \sigma_{0L}\sqrt{L}$, $L = 30$ mm. The second one is the collection time of the electron into the MWPC. It is obtained by drawing an x value (fig. 9a) randomly distributed in the interval $(0, s_0/2)$, to simulate the impact point of the electron at the separation electrode. The corresponding value of l is calculated from eq. (5) then multiplied by the adequate drift velocity $v(\text{MWPC})$ to derive the associated collection time. Let us call $\sigma_t(\text{simul})$ the standard deviation of this time distribution. Fig. 10 shows spectra obtained for the ratio l/l_0 and the stop time, in the case of $\sigma_D = 9$

* It can be shown that the “uniform” field strength in a MWPC, far from the wire, can be written: $E_{dc} = (\pi r_0/s)E_0$, where E_0 is the field strength at the wire surface, $E_0 = (V_0/r_0)(\pi l_0/s - \log 2\pi r_0/s)^{-1}$. Close to the wire, this field strength increases, but we shall assume that the drift velocity keeps along this short distance its saturated value.

Fig. 9. (a) Chamber parameters for the calculation of the length l of a field line. (b) Ratio l/l_0 vs the abscissa of the starting position at the cathode: $l_0 = 3$ mm, $s_0 = 2$ mm, $2r_0 = 15$ μ m.

ns. After adding the constant term $l_0 v_D(\text{MWPC})$, the Gaussian curve (σ_D), calculated at the separation electrode is superimposed to the corresponding [$\sigma_t(\text{simul})$] one. The peaks are separated by ~ 6 ns, as the mean l is larger than the MWPC gap l_0 and therefore the mean collection time larger than the constant term which was added. At low values of σ_D , ≤ 12 ns, the $\sigma_t(\text{simul})$ distribution has a positive skewness, or a tail on its right edge as was observed in fig. 8d. This skewness is less pronounced, the larger the velocity $v(\text{MWPC})$. This is apparent in fig. 11 where a comparison between measured and calculated σ_t distributions is shown: Fig. 11a relates to A-CH₄ 20%, $v(\text{MWPC}) = 35$ mm/ μ s and fig. 11b to pure methane where $v(\text{MWPC})$ is 54 mm/ μ s. The momenta of skewness are respectively 0.16 and 0.12. In fig. 12, we have a plot showing the standard deviation σ_D (diffusion alone) expected from a "measured" value σ_t . One sees that at σ_t larger than 12 ns, the electron collection time contributes for $\leq 10\%$, to reach 20% when $\sigma_t = 8$ ns. One can verify from several choices of σ_D and their corresponding σ_t that a relation such as $\sigma_t^2 - \sigma_D^2 = \text{constant} = C$ is satisfied. It can then be assumed that the effect of the collection time fluctuation is equivalent to a convolution of the diffusion distribution with a normal distribution having an rms equal to $\sqrt{C}$; let us call it $\sigma(\text{stop})$. One finds this quantity varying from 4 to 6 ns for the respective values of $v(\text{MWPC})$ of 40 to 60 mm/ μ s.

Fig. 10. a) l/l_0 distribution from starting points uniformly distributed at the cathode: $l_0 = 3$ mm, $s_0 = 2$ mm, $2r_0 = 15$ μ m. 5000 events with $x/x_0 \leq 0.99$ mm. b) simulated stop time distribution including diffusion and collection time fluctuations into the MWPC (5000 events). The pure diffusion (σ_D) distribution, shifted by $l_0 v(\text{MPWC})$ is superimposed.

Fig. 11. Measured and calculated stop time distributions. a) A-CH₄ 20%, $E = 800$ V/cm, $v_D = 44.2$ mm/ μ s. b) pure CH₄, $E = 416$ V/cm, $v_D = 84$ mm/ μ s.

5. Results and discussion

Figs. 13–18 show our results on the field strength dependence of drift velocities and coefficients of longitudinal diffusion for the different gas mixtures. Each of these curves originate from a given set of measurements, as these sets have been found reproducible within about a per cent for v_D and one bin for time distributions when they were repeated during several days at stable gas flow condition. No corrections have been applied about pressure and temperature which were typically (725 ± 1) Torr and $(22 \pm 2)^\circ\text{C}$. As seen on the velocity

Fig. 13. Drift velocity and longitudinal diffusion in argon-ethane 50%.

Fig. 12. R.m.s. of the diffusion distribution σ_D expected from a measured stop time distribution σ_t which includes the collection time fluctuation at various v (MWPC).

curves, the drift times range from ~ 300 ns (pure CH₄) to more than $10 \mu\text{s}$. As the systematic sources of error (a), (c), (d) and (e) contribute only a few nanoseconds, the accuracy on v_D is dominated by the relative contribution (b). In the limits of possible remaining systematic error sources (internal outgassing, field inhomogeneity) we shall fix the error on v_D to be less than $\pm 2\%$.

We compare our measurements with those already published in the same field range. A good agreement is found for drift velocity in argon-ethane fig. 13 with the results of Daum [1], Jean-Marie [2], Becker [14] at $E = 300$ – 1000 V/cm, and in pure methane (fig. 14) with Wagner [15], Lehraus [16], Daum [1], all these authors using clusters of electrons. In the case of argon-methane (fig. 15), we find a velocity slightly smaller ($\sim 4\%$) than in ref. 2, but with a larger difference compared to the result of Lehraus [17] ($\sim 10\%$). We repeated these measurements with high purity premixed gases ($\text{H}_2\text{O} < 2$ ppm, $\text{O}_2 < 0.5$ ppm) and a mixture made from separated bottles without observing significant variations in our results. If gas purity is questionable, it is clear that the most likely source may originate from a contamination inside the chamber vessel itself. About argon-CO₂ (fig. 17), also issued from high purity premixed gases, one observes a good agreement with the recent results of

Fig. 14. Drift velocity and longitudinal diffusion in pure methane.

Becker [14], 5% difference with Lehrs [16] (larger at high field) but a significant disagreement with Allison [8].

About the accuracy achieved on σ_{0L} , let us first remark that the statistical error on σ_i is proportional to $1/\sqrt{2N}$, where N is the number of events recorded in a distribution. This number has always been taken larger than 5000, leading to an error less than a per cent. The contribution of the electronic time jitters are also found negligible. Therefore the error on σ_{0L} ($\hat{=}\sigma_i v_D$) depends essentially on the relative values of σ_i with respect to the systematic quantities σ_{start} and σ_{stop} , estimated in the preceding section. These ones are reported (dashed line) in fig. 19, together with the measured values of σ_i in some gas mixtures. It can be seen that the largest values of σ_i are, by far, observed in argon- CO_2 and also in case of any methylal admixture but over a smaller field range. In binary mixtures, argon (neon)-methane (ethane), σ_i drops much earlier, ~ 150 V/cm, to values as small as 10–12 ns. However, as the drift is substantially slower in CO_2 or methylal mixtures, this leads to the smallest values of σ_{0L} but also to the best accuracies, as σ_i is large compared to the systematic error levels.

Fig. 15. Drift velocity and longitudinal diffusion in argon-methane 20%.

These remarks illustrate that the accuracy of the TOF method on the diffusion coefficient is not related in an obvious way to the size of this coefficient. We indicated on the plots of figs. 13 and 17, the values of σ_{0L} calculated from σ_i (circles) and those (crosses) obtained by subtracting the appropriate contributions of σ_{start} and σ_{stop} according to

$$\sigma_i^{corr} = \sigma_i \sqrt{1 - c^2/\sigma_i^2},$$

where

$$c^2 = \sigma_{start}^2 + \sigma_{stop}^2.$$

In figs. 14–16 and 18 the current values of c^2 are indicated. The relative error on σ_i^{corr} is now related to the error Δc done on the estimation of the systematic sources by

$$\frac{\Delta \sigma_i^{corr}}{\sigma_i^{corr}} = \frac{\Delta \sigma_i}{\sigma_i} (\text{measured}) + \frac{c}{\sigma_i^2 - c^2} \left(\Delta c + c \frac{\Delta \sigma_i}{\sigma_i} \right).$$

The values of c^2 used for each gas mixture are indicated in figs. 13–18. With $\Delta c \approx 1$ ns and $\Delta \sigma_i/\sigma_i$ (measured) $\approx 10\%$, the values of c^2 and σ_i (fig. 19a) allow an estimate of this error, found between 12–30%.

It is known [18,19] that in pure CO_2 , the electron

Fig. 16. Drift velocity and longitudinal diffusion in neon-methane 20%.

energy ϵ_k remains equal to its thermal value kT up to a field strength of about 800 V/cm at atmospheric pressure. The same observation is made in methylal [19] but

Fig. 17. Drift velocity and longitudinal diffusion in argon-CO₂ 20%.

Fig. 18. Drift velocity and longitudinal diffusion in various mixtures of argon (neon)-methane-methylal.

over a reduced field range, 300 V/cm. This implies a linear dependence of the drift velocity with the field expressed as $v_D = \alpha E/p$ with $\alpha = 0.549$ and 0.56 respectively in CO₂ [15] and methylal [20]. The units are $\text{cm}/\mu\text{s}$ and $\text{V}/\text{cm} \cdot \text{Torr}$. In addition, the diffusion ought to obey $\sigma_{0L} = \sqrt{2} kT/eE$ and from the relation in sect. 2.1, σ_i should depend on the field as $E^{-3/2}$ or

$$\sigma_i = p/\alpha\sqrt{2kTl}/e E^{-3/2}.$$

These relations can be used to check our measurements in mixtures containing these components, assuming that the adjunction of a noble gas is of no influence in a certain field range to be determined.

We have drawn in fig. 17 the velocity corresponding to pure CO₂ at the partial pressure which was used, 20% CO₂ at 725 Torr. The measurements in the mixture follow this straight line from 0 to ~ 250 V/cm but increase more rapidly at higher field. In the same field range, the diffusion decreases accordingly to a "kT" behaviour and then begins to increase about when the initial slope of the velocity curve changes. The same observations are made in the ternary mixtures, argon (neon)-methane-methylal (fig. 18), but the thermalized

Fig. 19. (a) Variation of the r.m.s. of the time distribution σ_t vs field strength in different gas mixtures: (●) A-CO₂ 20%; (+) A-CH₄-methylal; (×) A-ethane 50%; (○) A-CH₄ 20%; (Δ) methane. (b) The same variation as in (a) in log-log coordinates. (●) A-CO₂ 20%; (□) (+) A-methane-methylal; (×) Ne-CH₄ 20%; (○) A-CH₄ 20%; (Δ) methane.

behaviour stops around 100 V/cm. Again, one can check that the initial velocities are compatible, in the limits of accuracy of the methylal percentage determination, with the velocities calculated in pure methylal at E/p values corresponding to the working partial pressure. Finally, the $E^{-3/2}$ dependence of σ_t is observed at low field in the log-log diagram of fig. 19b, which is not the case for binary mixtures.

Therefore, the expected “ kT ” behaviour is well verified but the presence of a noble gas reduces the field range of thermalization associated to the pure component.

We compared our diffusion measurements with existing data in two cases. In argon-CO₂ 20%, where the best accuracy is achieved, a fair agreement is found, beyond the kT region, with Allison [8] (rise time measurements) and the Berkeley group [7] (TPC) while Ullaland’s results [21] (peak/valley ratio in ⁵⁵Fe spectra) are smaller in some places. In pure methane, where σ_t reaches its minimum value, our measurements agree with Wagner [15] and Forester [22] data at the exception of a field region around 250 V/cm where our value is significantly higher.

Coming back to fig. 19a, we see that the constant value reached by σ_t at high field is found not very different in all the mixtures under investigation, that is 10 ± 2 ns at $L = 30$ mm. The shape of the variation of σ_{0L} is then dictated by the variation of v_D , taking into account its relative position and steepness in the convolution with σ_t .

Most of these measurements were carried out in order to investigate “slow gas mixtures” suitable for primary cluster counting. The interest in neon comes from the fact that these clusters are better separated as the energy loss of a minimum ionizing particle is a half of the one in argon. The drift velocity convenient in such an experiment ranges between 3–8 mm/μs, therefore a good mixture is the one keeping the lowest velocity at the highest field strength to take benefit of the σ_{0L} decrease on $E^{-1/2}$ but still remaining in the thermalized region. Best results are obtained in argon-CO₂ (fig. 17). A large methylal admixture gives also interesting results but its concentration, which governs the drift velocity, is not so easy to stabilize. The choice of any noble gas, argon or neon, is of little influence both on velocity and diffusion.

6. Improvement of the method

For this purpose, the minimum value of σ_t (10 ± 2 ns at $L = 30$ mm) can be considered as a figure of merit to be compared to the main systematic sources of error, σ_{start} and σ_{stop} , achievable in a TOF set-up. Pulsed UV laser might be considered for decreasing σ_{start} .

We made the following attempt to reduce σ_{stop} . The mesh separations electrode was replaced by an aluminium foil having a slit, 1 mm wide, centered on the detection wire, thus avoiding the collection along the longest field line into the MWPC (wire distance: 2 mm). In argon-methane we observed at high field narrower time distributions but still slightly asymmetric. One can think that such a configurations allows a more pronounced penetration of the MWPC field into the drift gap together with edge effects around the slit. We preferred then to improve the set-up in a more drastic way which is under completion. A thin hole ($\varnothing 50$ μm) is drilled into the outer drift electrode and the UV flash

is now focused on it from the backside. The starting point of the photoelectron (lips of the hole) is now accurately defined together with its orthogonal projection on the detection wire. It is then possible to localize along this wire the impact point of the electron by measuring the centre of gravity of the induced charge distribution by means of cathode strips orthogonal to the wire. This allows us an independent measurement of both longitudinal and transverse diffusions.

An improvement on σ_{stop} is made by recording the pulse heights of the induced signals on the two adjacent wires and selecting those events having these amplitudes in a ratio close to 1. The drift distance can also be increased as the lateral diffusion is under control ($L = 90$ mm).

7. Conclusion

A time-of-flight method was used to measure drift velocities and coefficients of longitudinal diffusion of a single electron in several gas mixtures at 725 Torr. The measurements, performed in a field range of 0–1 kV/cm and 30 mm of drift, have shown the following points:

- A good accuracy $< \pm 2\%$ and stability can be achieved on the determination of drift velocities up to 10 cm/ μ s.
- The standard deviation of the stop-time distributions reaches about the same minimum value in different gas mixtures (10 ± 2 ns), but at a field strength depending on the presence of cold quenchers (CO_2 or methylal where $\epsilon_k = kT$).
- This r.m.s. value (10 ns) includes the major source of error which is the fluctuation of the stop signal, originating from the electron collection time into the MWPC. In the present set-up, it contributes for 4–5 ns and might be reduced in a coming work.

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