Electron Attachment, Effective Ionization Coefficient, and Electron Drift Velocity for CF_4 Gas Mixtures

W.S. Anderson, J.C. Armitage,[1] E. Dunn, J.G. Heinrich, C. Lu, K.T. McDonald, J. Weckel, and Y. Zhu

Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544

(February 10, 1992)

Abstract

For tracking in a SSC experiment with wire chambers, CF_4 gas mixtures are very advantageous from the point view of aging, drift velocity, and spatial resolution. However they are also known to suffer from considerable electron attachment. This attachment can cause serious inefficiencies in the collection of electrons liberated near the anode wire, and causes broadening of the pulse-height spectrum for all ionization electrons. Two bench-top set-ups have been used to study electron attachment of CF_4 gas mixtures, and related properties such as the gas-gain difference between single-electron avalanches and Fe^{55} x-ray initiated avalanches, the degradation of the energy resolution due to electron attachment, and the effective ionization coefficient $\bar{\alpha}$ ($\equiv \alpha - \eta$). A set of three prototype straw-tube modules each containing an 8×8 bundle of straws has been constructed and tested at a Fermilab test beam with various CF_4 gas mixtures. Some preliminary results on the drift velocity and drift time for these gas mixtures are reported.

(Submitted to the 6th International Wirechamber Conference, Vienna, 1992)

[1]Present address: Carleton U., Ottawa, Canada

Contents

List of Figures

List of Tables

1 Introduction

The "fast" gas CF_4 is believed to be one of the most attractive candidates for the SSC environment [1, 2]. Recent studies [3] have demonstrated a remarkable etching property of CF_4/isobutane mixtures, which suppresses the wire coating caused by avalanches in gases such as Ar/Ethane. Hence CF_4 gas mixtures show excellent aging performance [4, 5, 6]. But it is expected that CF_4 causes electron attachment. The perfluoroalkanes C_nF_{2n+2}, $(n = 1, 2, 3, 4)$ can serve as gaseous insulators because of their relatively large electron-capture cross section [7]. Electron attachment in a drift chamber will not only affect the detection efficiency, but also degrade the position resolution. A detailed Monte Carlo study of timing strategies in drift chambers[8] has concluded that the simplest approach is still the best: the best accuracy obtainable is based on first-electron timing.

Thus when evaluating the suitability of CF_4 gas mixtures for use at the SSC we need detailed understanding of the effects of electron attachment, as well as drift speed. We report here on a series of bench-top and test-beam studies of these properties of CF_4 gas mixtures.

2 Comparisons of Gas Avalanches Due to Single Electrons and Fe^{55} X-Rays

A sketch of the experimental set-up is shown in Fig. 1, which also gives details of the test chamber that permits both a laser beam and an Fe^{55} source to be used to generate the primary electrons. The N_2 laser generates pulsed 337-nm (3.67-eV) UV photons, with a pulse length of about 350 ps. The pulse energy is about 50 μJ, corresponding to about 10^{14} photons. The first test drift tube was made of 7.67-mm-diameter aluminum tubing, and later tubes of 3.3-, 4.83-, and 6.1-mm diameter were installed into this chamber. The laser beam passed through a 1-mm-diameter hole in the drift-tube wall, and was focused onto the inner wall of the aluminum tube, where the photoelectrons were generated. Using an iris diaphragm to adjust the beam intensity we were able to reduce the photoelectron rate to once every 10-20 laser pulses, and hence at least 99% of the recorded events were initiated by single photoelectrons. The output signal of the drift tube was amplified in an EG&G ORTEC model 142PC charge-sensitive preamplifier and recorded by a multichannel analyzer. A 20-μs-wide gate signal, triggered by a photodiode, was used to minimize system noise. With this there was no evidence for background pulses, and no background subtraction has been made in the data analysis. The electronics are sketched in Fig. 2.

The single-electron-avalanche spectra in Ar/isobutane, Ar/C_2H_6, Ar/CO_2, $Ar/CF_4/C_2H_2$, P-10, and CF_4/isobutane/C_2H_2 have been measured for several different mixing ratios. The single-electron-avalanche spectra were then fitted with the Polya distribution [9],

$$P(a) \propto (ba/\bar{a})^{b-1} e^{-ba/\bar{a}},$$

where a is the amplitude of an avalanche, $\bar{a}$ is the mean gas gain, and b is a measure of the fluctuation of gas gain: $(\sigma_a/a)^2 = 1/b$. Typical experimental distributions with their Polya fitting curves are shown in Fig. 3.

We were able to observe the presence of electron attachment in the chamber gas as follows.

Figure 1: Sketch of the experimental set-up and the test chamber.

Figure 2: Electronics for single-electron-avalanche measurements.

Figure 3: Single-electron-avalanche distributions with their Polya fittings for CF_4/isobutane/C_2H_2 (70/10/20).

Charge spectra were also recorded for each gas mixture at several different high voltages using an Fe^{55} source. If the signal size observed with the Fe^{55} source is not ~ 200 (= 5.9 keV/30 eV per ion pair) times that from a single photoelectron ejected by a laser pulse, then attachment has occurred. Comparisons of avalanches due to single photoelectrons with those from Fe^{55} x-rays are shown in Figs. 4 and 5. For the case of Fe^{55} we plot the gas gain as the observed pulse size divided by 200, the average number of primary electrons.

Conventional drift-chamber gas mixtures, such as Ar/C_2H_6, Ar/CO_2, P-10, and Ar/isobutane gave rather consistent results, both from single electrons as well as from Fe^{55} x-rays. This convinced us that the gas system had little contamination and the technique for single-electron-avalanche measurement was reliable.

Then when Ar/CF_4 gas mixtures were tested, the large discrepancy between single-electron and Fe^{55} measurements indicates that CF_4 may have serious electron attachment [1]. The gas gain from single electrons was about 5-12 times higher than that from Fe^{55}. The other gas mixtures containing CF_4 show similar behaviour, though the discrepancy may be not as big as with Ar/CF_4. This indicates that careful studies of different CF_4 gas mixtures are needed to determine which has the smallest electron attachment.

3 Degradation of the Energy Resolution Due to Electron Attachment

Additional evidence for electron attachment is the poor energy resolution observed with CF_4 gas mixtures. Previous work [1] yielded energy resolutions with Ar/CF_4 (95/5), and (90/10) of $\sim 60\%$, and $\sim 75\%$, respectively. We have measured the energy resolution for

Figure 4: Gas gain from single photoelectrons and from Fe^{55} x-rays. **(a)** Ar/C_2H_6 (50/50), **(b)** Ar/isobutane, **(c)** P-10, **(d)** Ar/CO_2 (50/50).

several conventional drift chamber gases and for CF_4 gas mixtures with typical values as summarized in Table 1.

Apparently the energy resolution for each category of CF_4 gas mixtures worsens with increasing gas pressure and with increasing percentage of CF_4. In contrast, no dependence of energy resolution on gas pressure was observed for conventional drift chamber gases.

A statistical model of the energy resolution of proportional counters has been well established. There are two basic contributions to fluctuations in the signal A: variations in the number n_0 of primary electron-ion pairs, and variation in size a of a single-electron avalanche.

Figure 5: Gas gain from single photoelectrons and from Fe^{55} x-rays. **(a)** Ar/CF_4, **(b)** CF_4/isobutane, **(c)** CF_4/isobutane/C_2H_2, **(d)** CF_4/C_2H_2 (90/10), **(e)** $Ar/CF_4/C_2H_2$.

Table 1: Energy resolution of various gas mixtures using an Fe^{55} source.

	P (Torr)	Gas Gain	Resolution (Fe^{55})
Ar/CH_4			
90/10	760	217	14.6%
	1360	301	15.3%
	1960	148	15.5%
Ar/C_2H_6			
50/50	760	440	16.3%
	1960	253	16.3%
Ar/isobutane			
80/20	760	206.0	16%
	1160	377.1	18.4%
	1960	243.8	17.3%
90/10	760	188.5	13.3%
	1160	2564.0	12.5%
	1960	1861.0	15.2%
Ar/CO_2			
50/50	760	308	15.0%
	1360	284	18.5%
	1960	344	17.3%
Ar/CF_4			
80/20	760	98.8	48%
	1160	105.9	61%
	1960	107.2	82%
50/50	760	119.0	53%
	1160	92.2	63%
	1960	89.1	98%
CF_4/isobutane			
80/20	760	2089	33.9%
	1060	2100	37.4%
	1960	1241	46.8%
60/40	760	1709	22.9%
	1160	1544	26.1%
	1960	1426	31.6%
50/50	760	1297	21.5%
	1160	1106	22.3%
	1960	1580	26.9%

Table 1: Energy resolution of various gas mixtures using an Fe^{55} source (continued).

	P (Torr)	Gas Gain	Resolution (Fe^{55})
CF_4/C_2H_2			
90/10	760	1078.7	38.7%
	1960	1647.0	44.8%
CF_4/isobutane/C_2H_2			
80/10/10	760	310	31.9%
	1360	502	36.9%
	1960	274	49.5%
70/10/20	760	225	25.5%
	1360	162	32.0%
	1960	361	39.5%
$Ar/CF_4/C_2H_2$			
80/10/10	760	280	18.0%
	1360	309	19.7%
	1960	200	21.7%
70/10/20	760	218	19.4%
	1360	202	21.4%
	1960	409	21.3%

This can be expressed as the follows [10]:

$$\left(\frac{\sigma_A}{A}\right)^2 = \left(\frac{\sigma_{n_0}}{n_0}\right)^2 + \frac{1}{n_0}\left(\frac{\sigma_a}{a}\right)^2 = \frac{1}{n_0}\left(F + \frac{1}{b}\right).$$

where F is the Fano factor and b is the parameter of Polya distribution discussed previously. Typical values of F and b are 0.05-0.2 and 1-2, respectively. Since n_0 is the number of ion pairs created by the incident radiation,

$$n_0 = E/W,$$

where E is the deposited energy, and W is the average energy loss per ion pair created. For all of the gas mixtures we have tested, $n_0 \sim 200$ when using an Fe^{55} source. The Polya parameters b for all of the tested gas mixtures were greater than 1, as determined by our fits to the observed spectra.

Even under the worst case of F and b (but no electron attachment), the energy resolution for 5.9-keV x-rays still should be better than 18%. For all of the CF_4 gas mixtures the measured energy resolution is worse than this. We believe that the loss of resolution is due to a reduction by electron attachment in the number n_0 of primary electrons. This can be confirmed by plotting the energy resolution of Fe^{55} x-rays *vs.* the ratio of gas gains initiated

by single-electron and Fe^{55}, G_{se}/G_{Fe}, as in Fig. 6. Recall that $G_{Fe} \equiv A_{Fe}/200$. Then G_{se}/G_{Fe} should be inversely proportional to the number of primary electrons due to the Fe^{55} source that contribute to the gas gain. The data points can be fitted by a line of slope ~ 0.5 on a log-log plot. This is a direct evidence of

$$\left(\frac{\sigma_A}{A}\right)^2 \propto \frac{1}{n_0}.$$

Extrapolating these lines to $G_{se}/G_{Fe} = 1$, we get a similar energy resolution of $\sim 18\%$, indicating that if the CF_4 mixtures had no electron attachment they would provide the same resolution as conventional mixtures.

4 Direct Measurement of the Effective Ionization Coefficient $\bar{\alpha}$

4.1 Experimental set-up

When an electron drifts in a gas with a gain coefficient α (= first Townsend coeficient = probability of creating an additional ion pair per unit length) and an attachment coefficient η (= probability of attachment per unit length), then the growth of the avalanche can be described by an effective ionization coefficient $\bar{\alpha} = \alpha - \eta$.

We have measured $\bar{\alpha}$ in various gas mixtures, using slightly different techniques for cases when $\bar{\alpha}$ is positive or negative. When $\bar{\alpha}$ is positive essentially every primary electron survives to be detected, and we use our technique of single-electron avalanches. But when $\bar{\alpha}$ is negative many primary electrons become attached and do not produce avalanches; here we must use a method where the observed signal is normalized to the number of primary electrons. Both cases were studied using a two-stage parallel-plate avalanche chamber, as shown in Fig. 7.

The aluminum cathode plate, five field-shaping rings, and the ground mesh were connected to a voltage divider to form a uniform electric-field region 3 cm in length. The open area of these electrodes was 5×5 cm^2.

The second section of the chamber is the 3-mm-long gap surrounded by the stainless-steel wire mesh (biased at ground potential) and the anode wire mesh (at positive high voltage). The fields in the second section were always much larger than in the first section, so the former was called the 'avalanche region', although small avalanches could occur in the first region as well. The meshes were approximately 80% transparent. Photoelectrons were ejected by UV photons both from the aluminum cathode plate as well as from the grounded mesh (which had a thin layer of aluminum evaporated on its surface to enhance its photosensitivity). Even though the aluminized ground mesh had an area 20% of the cathode plane, its observed effective quantum efficiency was only 2.5% that of the ground plane, as the aluminization was extremely thin .

The drift chamber was enclosed in a stainless-steel vacuum chamber, which could be pumped down to 10^{-6} Torr. The chamber was illuminated with UV photons through a quartz window. The signal for the EG&G 142PC preamplifier was taken from the anode wire mesh through a 2000-pF blocking capacitor.

Figure 6: Energy resolution of Fe^{55} *vs.* G_{Se}/G_{Fe}. **(a)** CF_4/isobutane, **(b)** CF_4/isobutane/C_2H_2, **(c)** Ar/CF_4/C_2H_2. For each gas mixture, three data points represent three different pressures, 760, 1360, and 1960 Torr, from left to right, respectively.

A bench-top gas system was built to mix different gas mixtures. This consisted of an MKS model 147 flow/pressure controller, model 1359 mass flow controllers, and model 250 valve. The mixed gas went through a Nanochem model L-60 gas filter designed to remove oxygen, water vapor, and other impurities before finally reaching the test chamber. According to the manufacturer, the gas filter is able to eliminate impurities to the low parts per billion range. The pressure in the chamber was monitored with an Edwards model 600A pressure transducer with a quoted resolution of 1 part in 10^4. The water vapor level in the chamber

Figure 7: Two-step PPAC used for $\bar{\alpha}$ measurement.

was monitored with a Kahn moisture meter. The meter read water vapor levels in parts per million to a quoted accuracy of approximately ± 4 ppm. The gas purity in our measurement was CF_4 99.99%, Ar 99.999% according to the vendor.

4.2 Experimental method and results

In the first part of the study we used low-intensity deuterium lamp so that we observed only single-electron avalanches. For this the intensity was reduced until the signal rate from the chamber was only 10-1000 Hz. The aluminum cathode was set at ground potential, there was no electric field between cathode and the ground mesh. Therefore the photoelectrons generated at the cathode were not able to reach the avalanche region (as verified by observing no change in signal when a small positive voltage was applied to the cathode plane). All of the measured events were initiated by the photoelectrons released from the aluminized ground mesh. The spectra were then fitted with the Polya distribution to get the average gas gain G. The density-normalized effective ionization coefficient $\bar{\alpha}$ was calculated as $\ln G/Nd$, where N is the gas density, and d is the gap length.

Because we used a mesh to separate two electric field regions, the shielding inefficiency of the ground mesh has to be considered. According to O. Bunemann *et al.*[11] the shielding inefficiency σ, which is defined as dE_1/dE_2, where E_1 and E_2 are the electric field strength of two regions separated by the grid, is very small for the geometry of our chamber and mesh,

$\sim 0.1\%$. Therefore the electric field of the avalanche region is simply equal to the applied positive voltage on the anode mesh divided by the gap length. No correction is necessary.

In order to avoid the secondary avalanche due to feedback of UV photons onto the cathode, the gas gain was limited to be less than 10^4. On the other hand, unless the gas gain were greater than about 2000 the single-electron signal was to small to be analyzed. The gas pressure was varied from 5 to 200 Torr and for each pressure data were collected at high voltages such that the avalanche size fell within the mentioned range.

To measure the effective ionization coefficient $\bar{\alpha}$ at low values of E/P, where for some gas mixtures a negative value of $\bar{\alpha}$ was expected, it was not possible to use the single photoelectron method which is blind to primary electrons that become attached. Instead, a second method utilizing both regions of the drift chamber was adopted. The gas pressure of the chamber was set at 5 Torr to make it easier to cover a large range of E/P. The positive high voltage in the avalanche region was fixed for each of the gas mixtures. The electric field in the drift region was then varied by adjusting the cathode potential. This ranged from 10 V to the upper limit at which breakdown took place.

For this second measurement the deuterium lamp was replaced by the pulsed N_2 laser, so that a large number of primary electrons were photoemitted during a 1-nsec interval. These photoelectrons drifted across the first gap of the chamber, and according to the value of E/P, different numbers fell victim to the attachment process before entering the second gap. The size of the avalanche produced in the second gap varied linearly with the number of entering electrons, since the gain in this region was held constant.

Some primary electrons were ejected from the aluminized ground mesh, and so were not subject to the possible attachment in the first gap that we wish to study. The resulting small ($\sim 2.5\%$), constant signal was subtracted from the total, which could then be interpreted in terms of $\bar{\alpha}$ for the first gap.

The region of E/P studied in the second method was partially overlaped by some data points measured with the single-photoelectron method. This overlap region was served as the normalization for the second method.

In contrast to the almost-exponential single-electron gain distributions, the gain distributions produced by the photoelectrons from the laser pulse were peaked around an average gas gain. Pulse-to-pulse variations in the laser were on the order of 1.5/measured with an RCA C30905E avalanche photodiode.

Pure CF_4, and Ar/CF_4 (80/20) were measured with this set-up, with results as shown in Fig. 8. The data from L.G. Christophorou *et al.*[12] are also shown in the same figure. For Ar/CF_4 (80/20) our result matches theirs very well. For pure CF_4 below $E/P = 60$ V/cm·Torr the agreement is good, beyond this value a small discrepancy appears.

From the measured $\bar{\alpha}/N$ in the parallel-plate chamber, we can calculate the probability of survival of an electron in a cylindrical proportional chamber to compare with the results of Fig. 6 above. For pure CF_4, $\bar{\alpha}$ becomes negative within the region $12 < E/P < 48$ V/cm·Torr. The survival probability P_s can be written as follows:

$$P_s = e^{\int_{r_1}^{r_2} \bar{\alpha}\, dr},$$

where the integration should be over the region of negative $\bar{\alpha}$. Using the relation $E =$

Figure 8: Effective ionization coefficient $\bar{\alpha}$ for CF_4 and Ar/CF_4.

$V/(r\ln(R_b/R_a))$, we arrive at

$$P_s = \exp\Big(\frac{V}{\ln(R_a/R-b)}\int_{e_1}^{e_2}\frac{(\bar{\alpha}/P)}{(E/P)^2}\,d(E/P)\Big),$$

where e_1, e_2 should be 12, 48 V/cm·Torr, respectively. We can roughly fit the $\bar{\alpha}/P$ *vs.* E/P data points with a quadratic function, so that P_s is readily calculated.

Fig. 6 shows the ratio of the single-electron gas gain to that with Fe^{55} x-rays for CF_4 under three different gas pressures: 760, 1360, and 1960 Torr. The high voltage were set at 2000, 2600, and 3100 V, respectively. The measured ratios are 9.26, 15.3, 34.8. The calculated values from the above formula are 7.4, 13.5, 22. The agreement is satisfactory, and confirms that our study of electron attachment provides sufficient information to predict the operation of cylindrical proportional chambers under a relevant variety of conditions.

Work is in progress to measure the electron attachment in a number of CF_4 gas mixtures, to aid in choosing the optimum gas mixture for future detectors.

5 Preliminary Results of Beam Tests of a Prototype Straw-Tube System

We have constructed a set of three prototype straw-tube modules each containing an 8×8 bundle of straws, for a total 192 channels. The straw tubes were 30 cm in length, and 7 mm in diameter, with 20-μm gold-plated tungsten anode wires. The readout electronics were based on the U. Penn bipolar preamplifier chip [13]. A LeCroy 4290 TDC system was used to digitize the drift times, which were recorded onto disk with a 486 PC-clone computer. A block diagram of the electronics system is shown in Fig. 9.

Figure 9: Block diagram of beam-test data-acquisition system.

Detailed data analysis now is underway. More complete description of the preamplifier card and data acquisition system will be reported in the future paper. Here we only present some preliminary results on the drift time and drift velocity for various gas mixtures.

The tested gas mixtures are listed in Table 2.

Table 2: Tested gas mixtures.

No.	Gas mixture	Mixing ratio
1	Ar/C_2H_6	50/50, 80/20
2	Ar/CO_2	80/20, 50/50, 20/80
3	CO_2/CH_4	20/80
4	CO_2/C_4H_{10}	80/20
5	Ar/CF_4	80/20, 50/50
6	$Ar/CF_4/C_2H_2$	70/20/10, 40/40/20
7	$Ar/CF_4/CO_2$	70/20/10, 80/10/10
8	CF_4/C_4H_{10}	100/0, 80/20, 50/50
9	$CF_4/C_4H_{10}C_2H_2$	80/10/10, 40/40/20

The beam size of test-beam line was bigger than 6×6 cm^2, which covered the whole area of the prototype. For each gas mixture and high voltage setting about 10^5 events were recorded. We plot the fitting curves of drift time *vs.* track impact distance for some of the gas mixtures in Fig. 10. The drift velocity can be derived by taking the derivatives of these fitting curves. Typical values are shown in Fig. 11.

For a high-rate SSC tracking device the longest signal-collection time should be the beam crossing interval, namely 16 ns. With the data of Fig. 10 we can choose a suitable tube size

Figure 10: Fitting curves of drift time *vs.* track impact distance.

Figure 11: Drift velocity obtained from the derivatives of the curves in Fig. 10.

to meet this requirement.

6 Summary

Electron attachment in CF_4 gas mixtures has been revealed by three experimental evidences:

- Gas-gain difference between Fe^{55}-x-ray-initiated and single-electron-initiated avalanches,
- Degradation of energy resolution for Fe^{55} x-rays,
- Direct measurement of the effective ionization coefficient $\bar{\alpha}$.

The beam test results of drift time *vs.* impact distance for various gas mixtures provide guideline for choosing a suitable straw-tube size for high-speed signal collection at the LHC and SSC.

7 Acknowledgements

The authors would like to express their gratitude to H. Edwards, Jr., W. Sands and R. Klemmer for their skillful design and manufacture of the test chambers.

8 References

[1] L.G. Christophrou *et al.*, *Fast Gas Mixtures for Gas-Filled Particle Detectors*, Nucl. Instr. and Meth. **163** (1979) 141.

[2] J. Fischer *et al.*, *Proportional Chambers for Very High Counting Rates Based on Gas Mixtures of CF_4 with Hydrocarbons*, Nucl. Instr. and Meth. A238 (1985) 249.

[3] R. Openshaw *et al.*, *Etching of Anode Wire Deposits with CF_4/isobutane (80/20) avalanches.* Proceedings of the Symposium on Detector R & D for the SSC, (Fort Worth, Texas, Oct. 1990).

[4] R. Henderson *et al.*, *Wire Chamber Ageing with CF_4/isobutane and Ar/Ethane mixtures.* IEEE **NS35** (1988) 477.

[5] R. Openshaw *et al.*, *Test of Wire Chamber Aging with CF_4/isobutane(80/20), Ar/Ethane(50/50), and Ar/Ethane/CF_4(48/48/4).* IEEE **NS36**(1989) 567.

[6] J. Kadyk, *Wire Chamber Aging*, Nucl. Instr. and Meth. **A300** (1991) 436.

[7] M.S. Naidu and A.N. Prasad, *Mobility, Diffusion and Attachment of Electrons in Perfluoroalkanes.* J. Phys. D: Appl. Phys. **5** (1972) 983.

[8] J. Va'vra, *Search for the Best Timing Strategy in High Precision Drift Chambers*, Nucl. Instr. and Meth. **225** (1985) 445.

[9] J. Byrne, *Statistics of the Electron Multiplication Process in Proportional Counters.* Proc. Roy. Soc. Edin. **66A** (1962) 33.

[10] G.F. Knoll, *Radiation Detection and Measurement, 2nd ed.*, (John Wiley & Sons, New York, 1989).

[11] O. Bunemann *et al.*, *Design of Grid Ionization Chamber*, Can. J. Res. **27** (1949) 191.

[12] L.G. Christophorou *et al.*, *Gases of Possible Interest to SSC Muon Detectors*, Nucl. Instr. and Meth. **A309** (1991) 160.

[13] F.M. Newcomer *et al.*, *A Fast Monolithic Preamp and Shaper for High Rate Gas Tracking Detectors*, U. Pennsylvania, preprint.