

Electron attachment, effective ionization coefficient, and electron drift velocity for CF_4 gas mixtures

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For tracking in a SSC experiment with wire chambers, CF_4 gas mixtures are very advantageous from the point of 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 setups 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 ^{55}Fe 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.

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 [4–6]. But it is expected that CF_4 causes electron attachment. The perfluoroalkanes $\text{C}_n\text{F}_{2n+2}$, ($n = 1, 2, 3, 4$) 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 ^{55}Fe X-rays

A sketch of the experimental setup is shown in fig. 1, which also gives details of the test chamber that permits both a laser beam and an ^{55}Fe 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, model 570 amplifier, 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.

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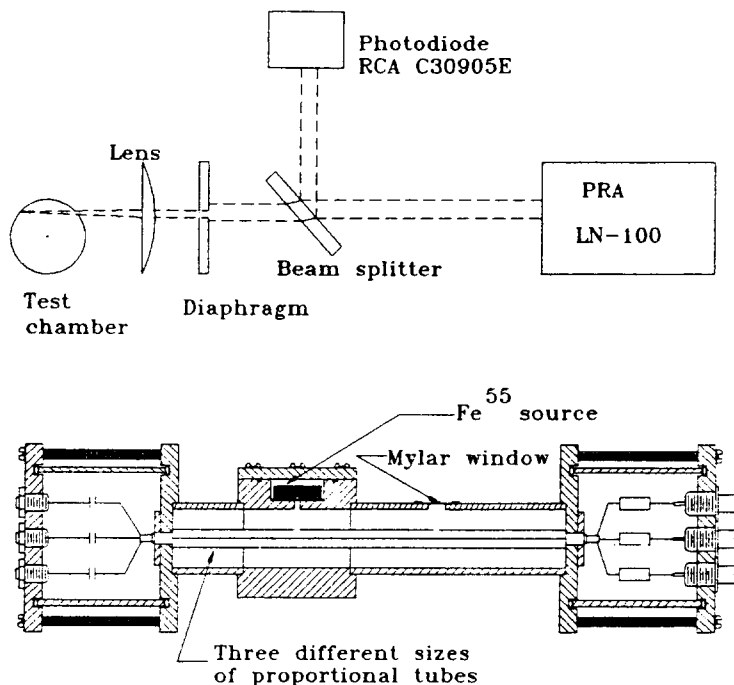


Fig. 1. Sketch of the experimental setup and the test chamber.

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. 2.

We were able to observe the presence of electron attachment in the chamber gas as follows. Charge spectra were also recorded for each gas mixture at several different high voltages using an ^{55}Fe source. If the signal size observed with the ^{55}Fe source is not ~ 200 ($= 5.9 \text{ keV}/30 \text{ eV}$ 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 ^{55}Fe X-rays are shown in figs. 3 and 4. For the case of ^{55}Fe 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 ^{55}Fe 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 ^{55}Fe measurements indicates that CF_4 may have serious electron attachment [1]. The gas gain from single elec-

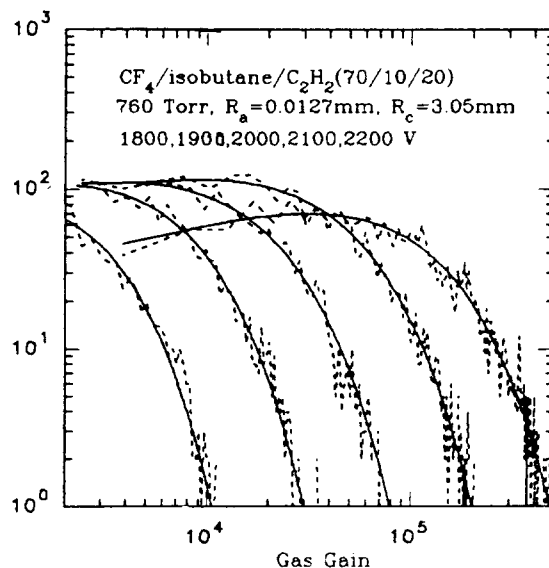


Fig. 2. Single-electron avalanche distributions for CF_4 /isobutane/ C_2H_2 (70/10/20).

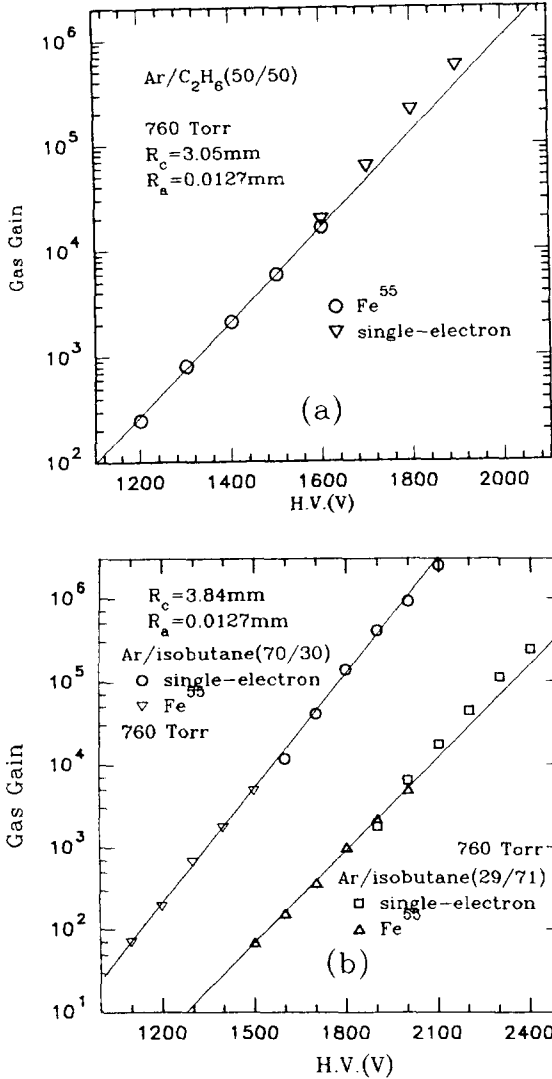


Fig. 3. Gas gain from single electrons and ⁵⁵Fe in some conventional gas mixtures.

trons was about 5–12 times higher than that from ⁵⁵Fe. The other gas mixtures containing CF₄ show similar behaviour, though the discrepancy may be not as big as with Ar/CF₄. This indicates that careful studies of different CF₄ 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 CF₄ gas mixtures. Previous work [1] yielded energy resolutions with Ar/CF₄ (95/5), and (90/10) of ~60%, and ~75%,

respectively. We have measured the energy resolution for 15 conventional drift chamber gases and for CF₄ gas mixtures at various pressures.

In particular, we found that the energy resolution for each category of CF₄ gas mixtures worsens with increasing gas pressure and with increasing percentage of CF₄. 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. This can be expressed as 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

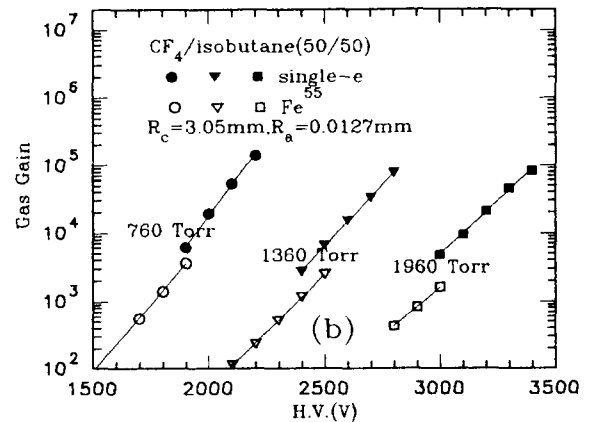
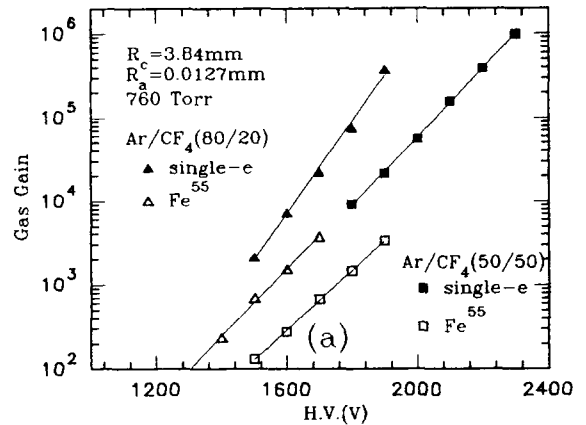


Fig. 4. Gas gain from single electrons and ⁵⁵Fe in some CF₄ gas mixtures.

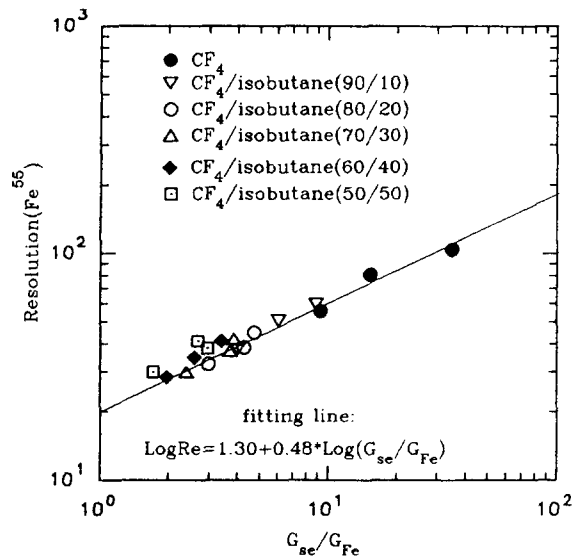


Fig. 5. Energy resolution of ⁵⁵Fe vs G_{sc}/G_{Fe} .

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 ⁵⁵Fe 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 CF₄ 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 ⁵⁵Fe X-rays vs the ratio of gas gains initiated by single-electron and ⁵⁵Fe, G_{sc}/G_{Fe} , as in fig. 5. Recall that $G_{Fe} \equiv A_{Fe}/200$. Then G_{sc}/G_{Fe} should be inversely proportional to the number of primary electrons due to the ⁵⁵Fe 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

$$(\sigma_A/A)^2 \propto 1/n_0.$$

Extrapolating these lines to $G_{sc}/G_{Fe} = 1$, we get a similar energy resolution of $\sim 18\%$, indicating that if the CF₄ 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 setup

When an electron drifts in a gas with a gain coefficient α (= first Townsend coefficient = 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. 6.

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 cm².

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

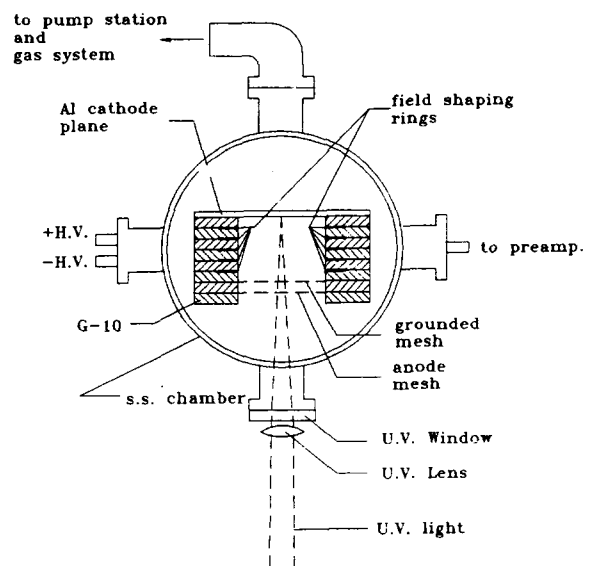


Fig. 6. Two-step PPAC used for $\bar{\alpha}$ measurement.

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.

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 a few 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 10⁴. The water vapor level in the chamber 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 CF₄ 99.99%, Ar 99.999% according to the vendor.

4.2. Experimental method and results

In the first part of the study we used a 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.

In order to avoid the secondary avalanches due to feedback of UV photons onto the cathode, the gas gain was limited to be less than 10⁴. On the other hand, unless the gas gain was greater than about 2000 the single-electron signal was too 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

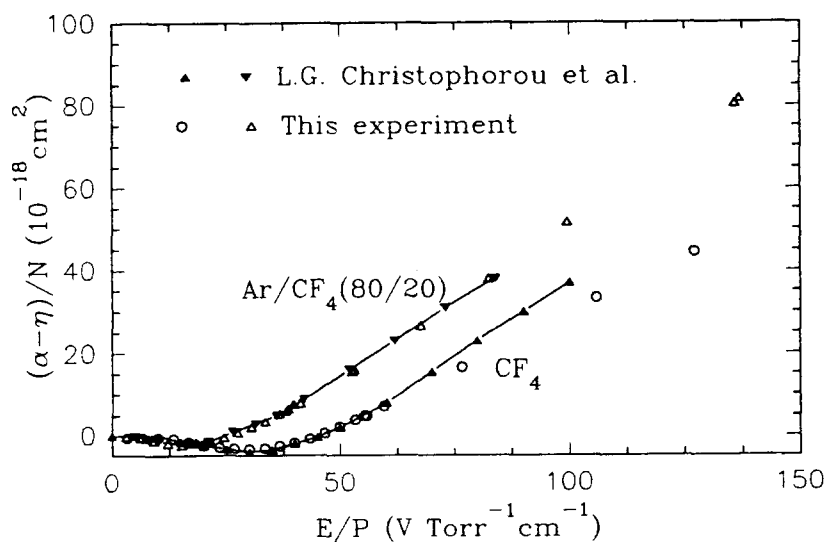


Fig. 7. Effective ionization coefficient $\bar{\alpha}$ for CF₄ and Ar/CF₄.

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 N₂ laser, so that a large number of primary electrons were photoemitted during a 1 ns 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 aluminumized 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 overlapped 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%, as measured with an RCA C30905E avalanche photodiode.

Pure CF₄, and Ar/CF₄ (80/20) were measured with this setup, with results as shown in fig. 7. The data from Christophorou et al. [11] are also shown in the same figure. For Ar/CF₄ (80/20) our result matches theirs very well. For pure CF₄ 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. 5 above. For pure CF₄, $\bar{\alpha}$ becomes negative within the region $12 < E/P < 48$ V/cm Torr. The survival probability P_s can be written as follows:

$$P_s = \exp\left(\int_{r_1}^{r_2} \bar{\alpha} dr\right),$$

where the integration should be over the region of negative $\bar{\alpha}$. Using the relation $E = V/(r \ln(R_b/R_a))$, we arrive at

$$P_s = \exp\left(\frac{V}{\ln(R_a/R_b)} \int_{e_1}^{e_2} \frac{(\bar{\alpha}/P)}{(E/P)^2} d(E/P)\right),$$

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. 5 shows the ratio of the single-electron gas gain to that with ⁵⁵Fe X-rays for CF₄ 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 CF₄ 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 Penn bipolar preamplifier chip [12]. A LeCroy 4290 TDC system was used to digitize the drift times, which were recorded onto disk with a 486 PC-clone computer.

Detailed data analysis now is under way. More complete description of the preamplifier card and data acquisition system will be reported in a future paper. Here we only present some preliminary results.

The beam size of test-beam line was bigger than 6 × 6 cm², which covered the whole area of the prototype. For each gas mixture and high voltage setting

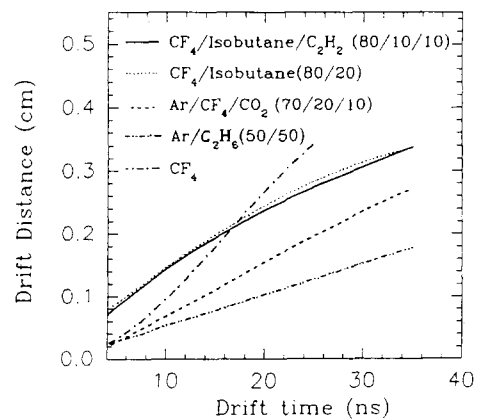


Fig. 8. Fitting curves of drift time vs track impact distance.

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. 8.

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. 8 we can choose a suitable tube size to meet this requirement.

6. Summary

Electron attachment in CF₄ gas mixtures has been revealed by three experimental evidences:

- gas-gain difference between ⁵⁵Fe X-ray initiated and single-electron initiated avalanches,
- degradation of energy resolution for ⁵⁵Fe 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.

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